Fundamental Symmetries: from the Table-Top to Colliders

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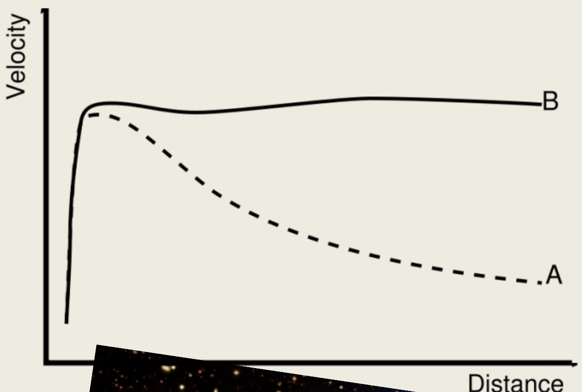
Previous @ Umass Amherst

The search for something non-Standard…

13.x billion years



Theoretical puzzles

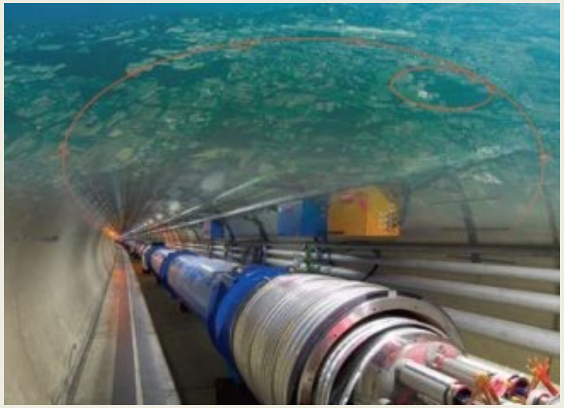
$$\frac{m_{Higgs}}{m_{Planck}} \sim 10^{-16}$$

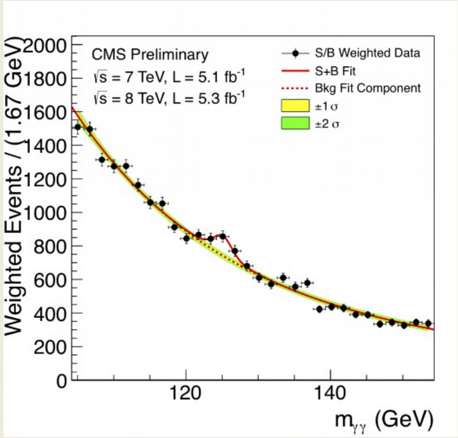
$$\theta_{CP} < 10^{-10}$$

The search for something non-standard…

Try to create something new directly

Energy





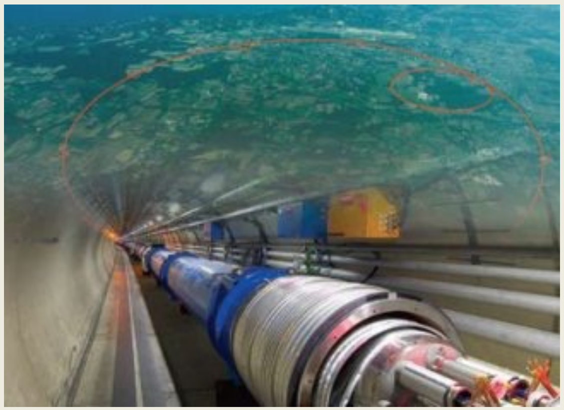
Reach ~ collider energy

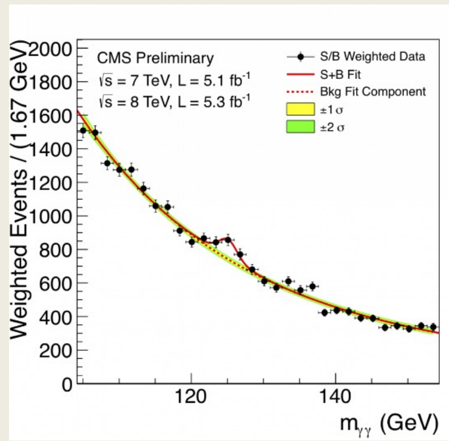
LHC, FCC, CEPC, ….

The search for something non-standard…

Try to create something new directly

Energy





Reach ~ collider energy

LHC, FCC, CEPC, ….

Indirect effects with precisely known (sometimes no) SM background

Examples are: Flavor, g-2, **EDMs**, $0\nu2\beta$, proton decay

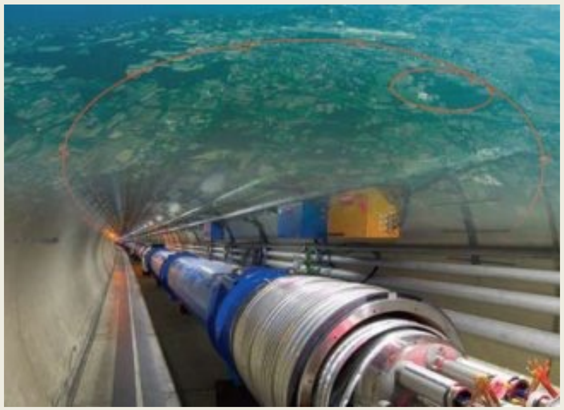
Colliders if BSM scale is too high

Reach ~ experimental and **theoretical** accuracy

Lot of excitement these days! (muon g-2, Flavor, W-mass, …)

The search for something non-Standard…

Energy



Complementary information

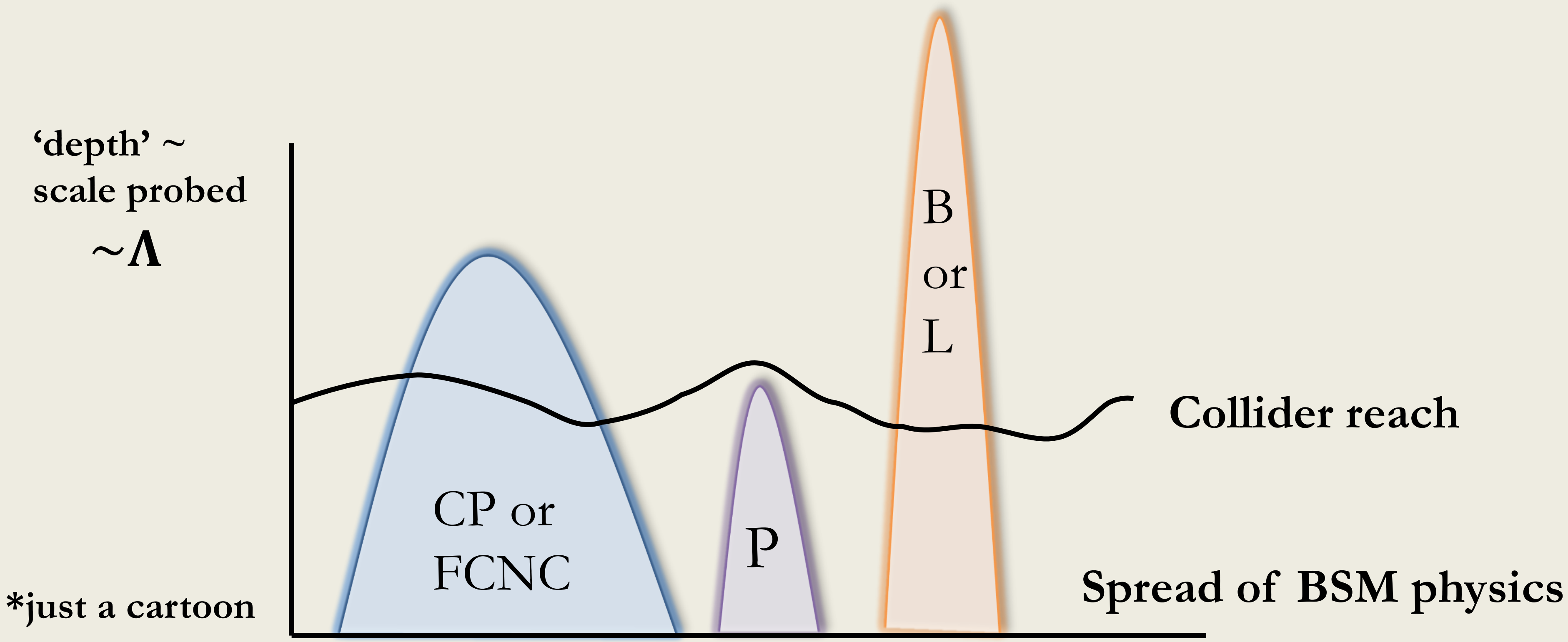
The search for something non-standard…

Collider experiment

- Not only discovery but dissemination (e.g. Higgs boson and its couplings)
- Broad search
- Difficult to reach BSM if scale >> TeV

Low-energy precision

- Typically smaller-scale and cheaper (not cheap)
- Can reach very high scales but…
- More limited scope
- Only so much we can learn



It's a large field of physics….

Will focus on a case where **hadronic/nuclear physics** play a big role

- $\Delta B = 1,2$ — Proton decay and neutron-antineutron oscillations
- $\Delta L = 2$ — Neutrinoless double beta decay
- $\Delta L_{e,\mu} = 1$ — Lepton-flavor violation e.g. $\mu N \rightarrow e\, N$
- Dark matter direct detections
- Many axion searches (e.g. CASPEr) + general ALP searches
- CP — **Electric dipole moments**
- P — Parity-violating electron-proton scattering (Qweak)
- P — Hadronic Parity violation
- C, P, T, CP — Neutron and nuclear β−decay experiments
- CPT — Tests of CPT and Lorentz symmetry
- ………….

Connections

1. We do not know if and what BSM physics exists. **How do we start?**

2. How to go from a scale TeV → GeV → MeV → eV experiments ?

3. Low-energy experiments often involve **low-energy QCD (hadronic and nuclear physics). How to handle this ?**

Goal of this talk: framework to connect low-energy experiments to 'particle physics' language ←→ connect to high-energy searches

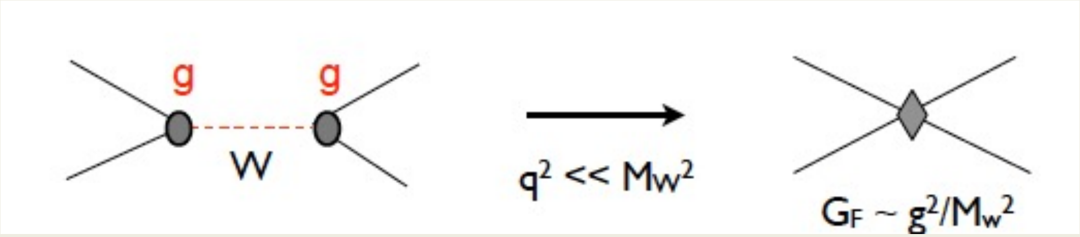
Effective Field Theories are a useful tool to attack 1, 2, and 3

Describing the unknown

Buchmuller & Wyler '86
Gradzkowski et al '10

- Assume BSM physics exists but is heavy → **Integrate them out**

Fermi's theory:



- We don't need 'high-energy details', the W boson, at low energies !

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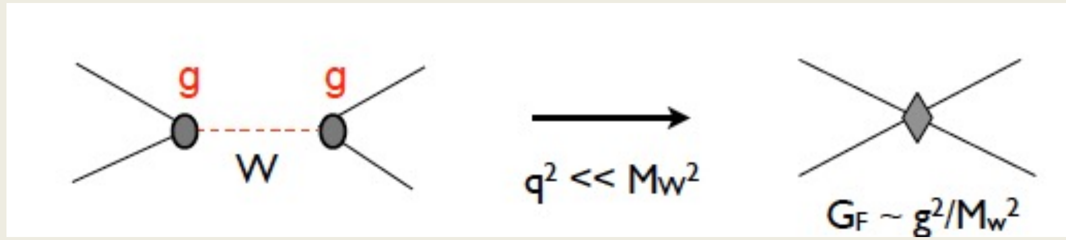

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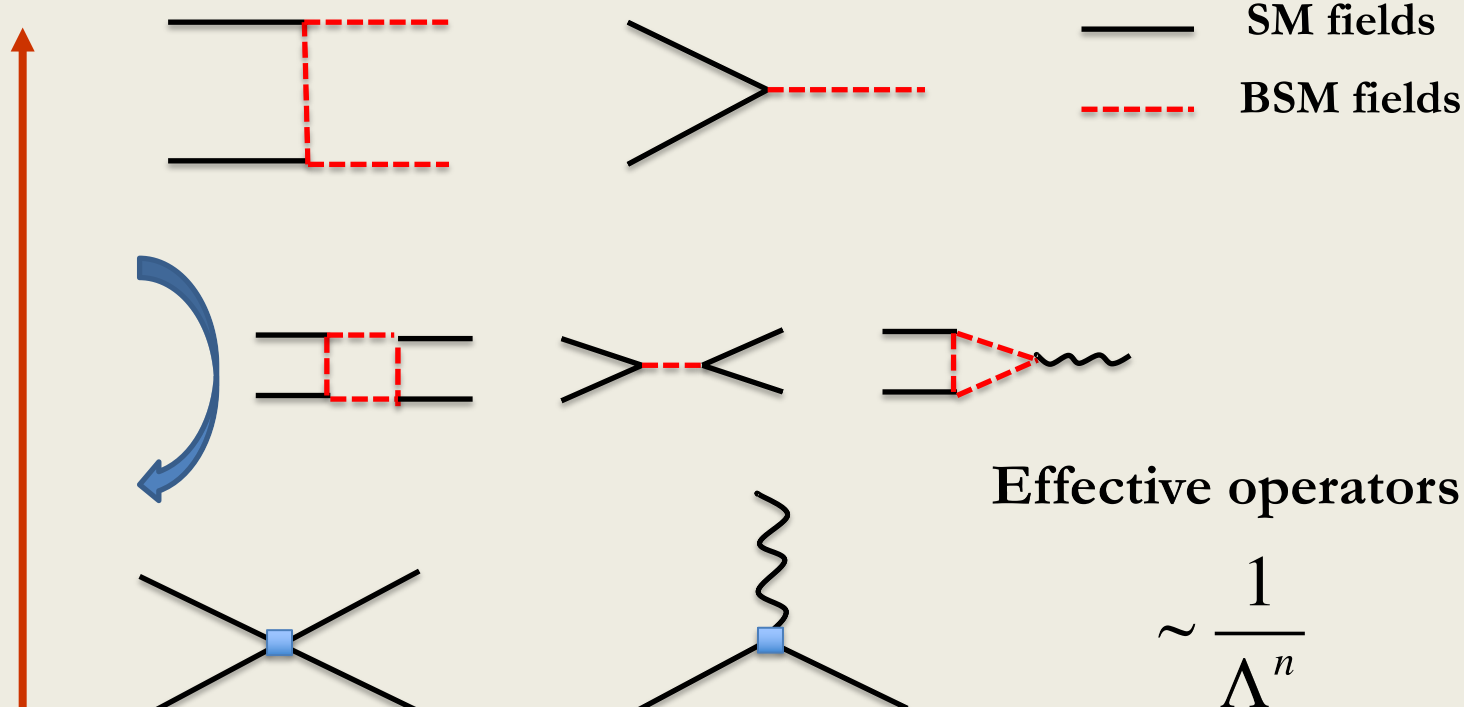
Energy

Λ



$E_{exp} << \Lambda$

Effective operators

$$\sim \frac{1}{\Lambda^n}$$

Describing the unknown

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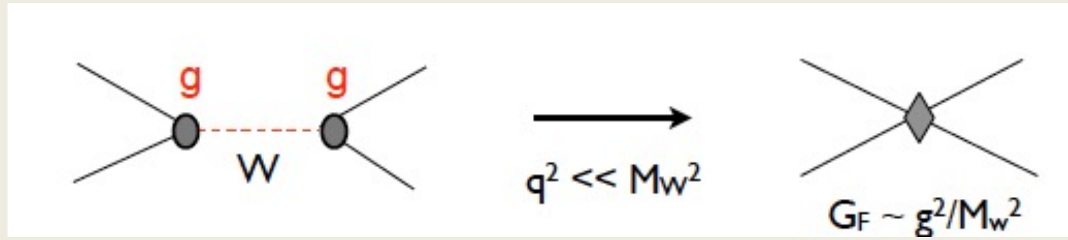
Fermi's theory:



- We don't need 'high-energy details', the W boson, at low energies !

Energy

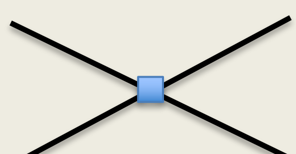
Not applicable for many interested cases: light sterile neutrinos, axions, stable relics,…

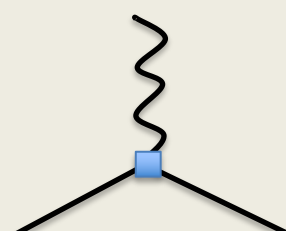
Λ

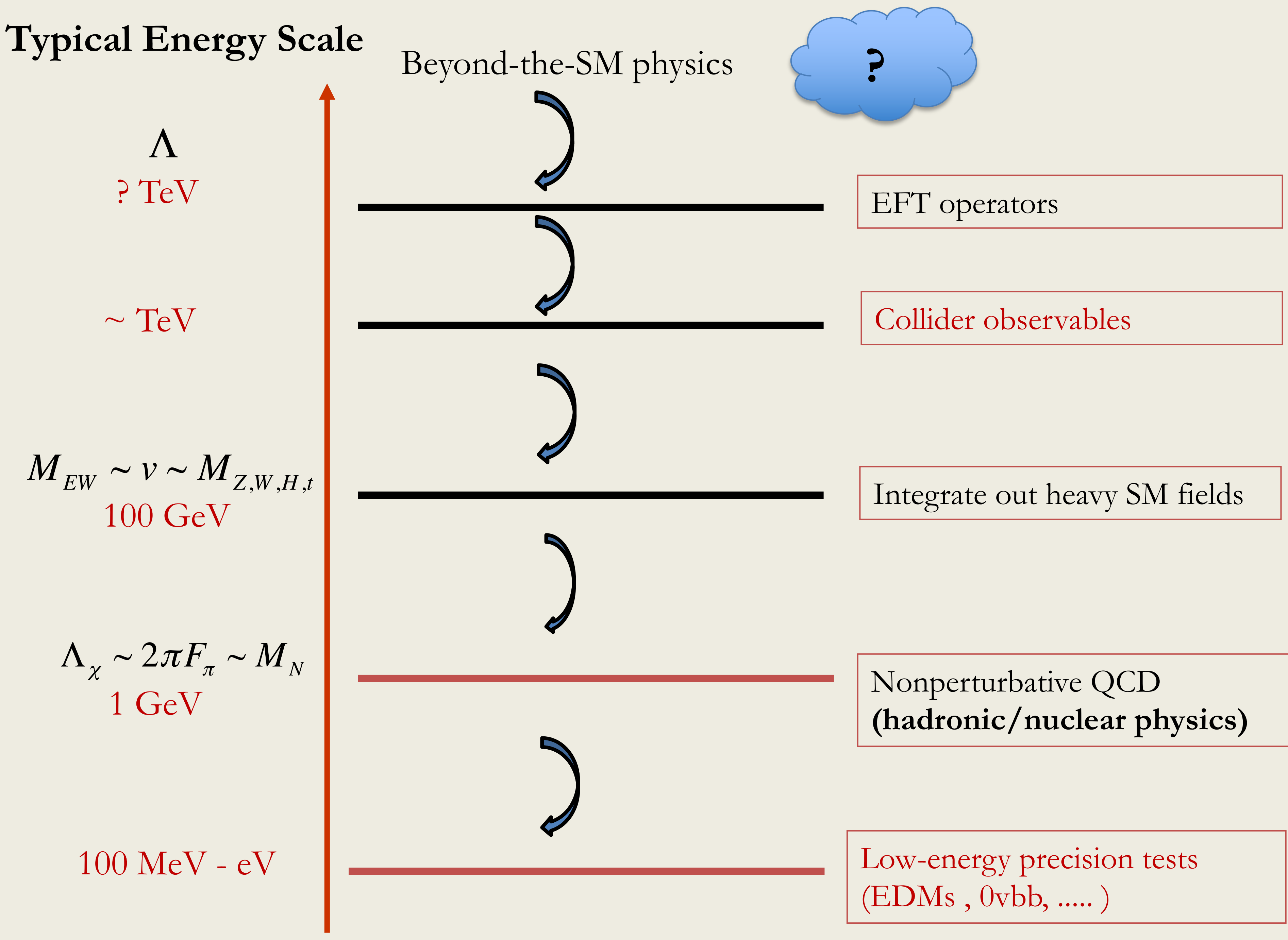
1) Degrees of freedom: All Standard Model fields
2) Symmetries: Lorentz and gauge: SU(3)xSU(2)xU(1)

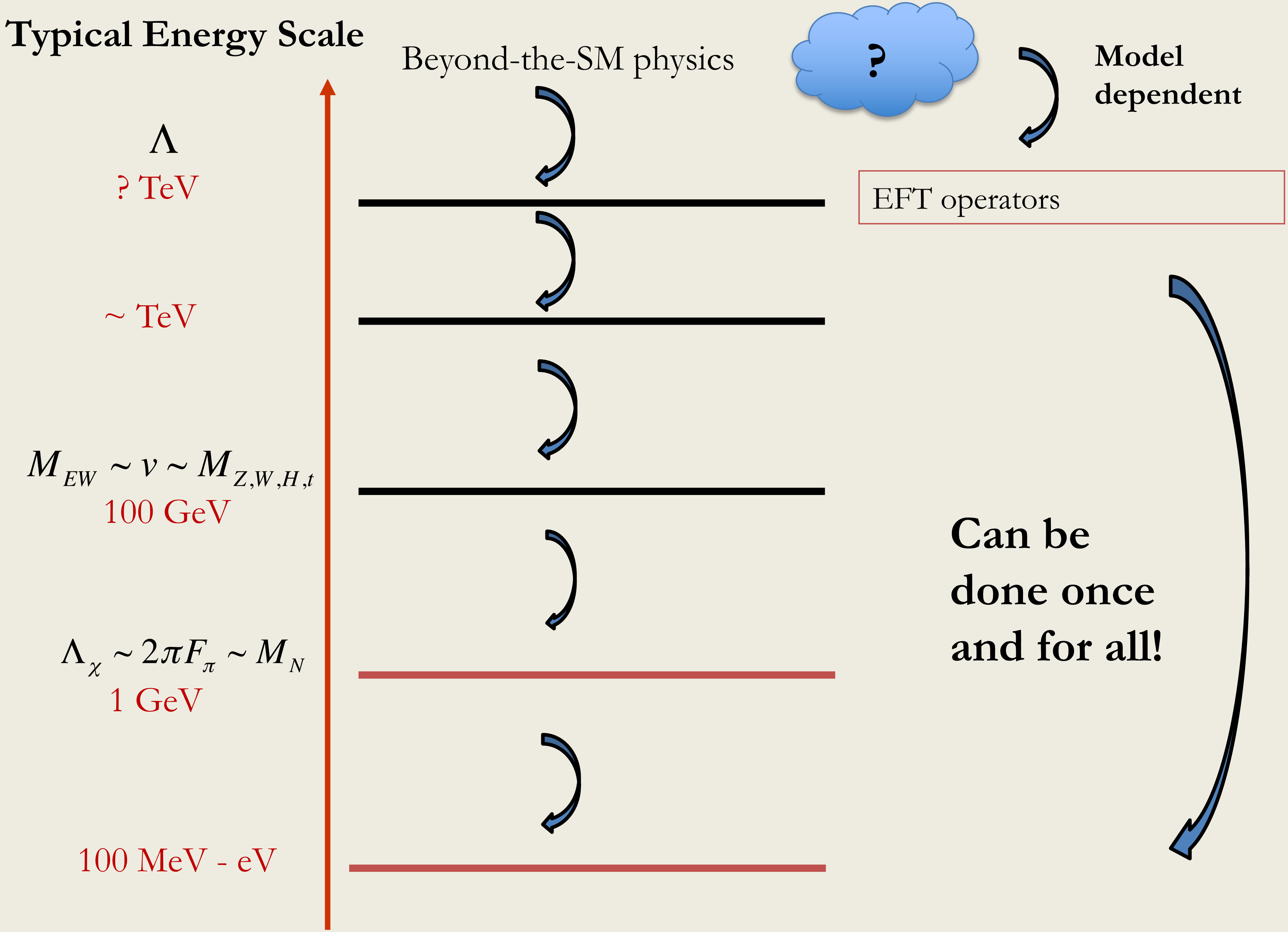
$$L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

$E_{exp} << \Lambda$





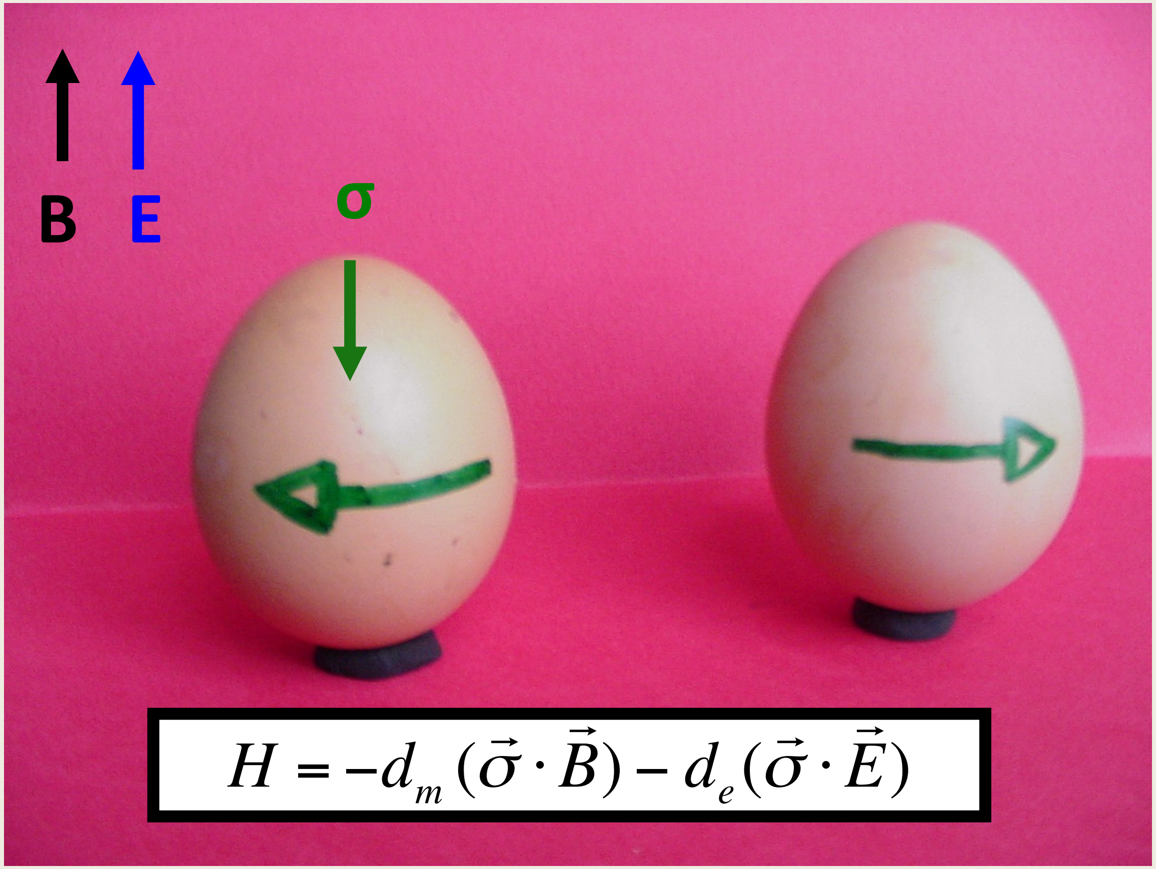

Typical Energy Scale
Beyond-the-SM physics
?
Λ
? TeV
EFT operators
~ TeV
Collider observables
$M_{EW} \sim v \sim M_{Z,W,H,t}$
100 GeV
Integrate out heavy SM fields
$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$
1 GeV
Nonperturbative QCD
(hadronic/nuclear physics)
100 MeV - eV
Low-energy precision tests
(EDMs , 0vbb, ...)



Typical Energy Scale
Beyond-the-SM physics
?
Model dependent
Λ
? TeV
EFT operators
~ TeV
$M_{EW} \sim v \sim M_{Z,W,H,t}$
100 GeV
Can be done once and for all!
$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$
1 GeV
100 MeV - eV

A worked out example: EDMs

- Electric and Magnetic Dipole Moment (EDM and MDM)

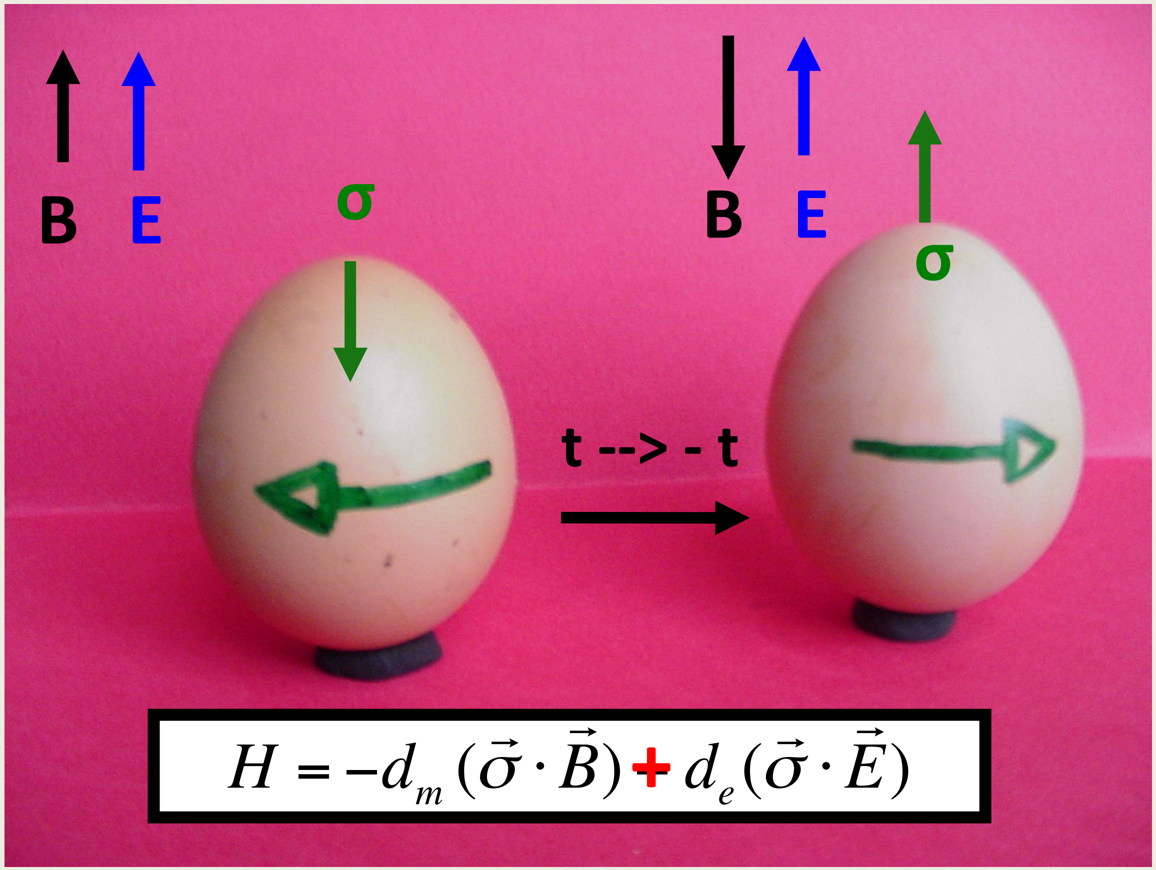


PhD Thesis: Hudson

A worked out example: EDMs

- Electric and Magnetic Dipole Moment (EDM and MDM)

Pauli

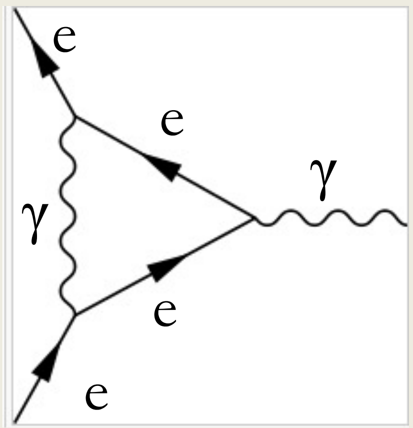


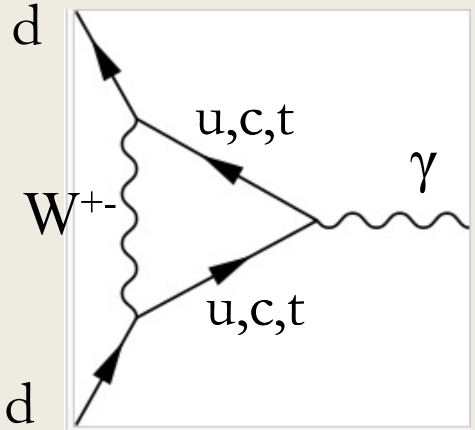
- The EDM, breaks time-reversal symmetry ! No EDM in QED at all
- **CPT theorem:** T violation ⟷ CP violation

PhD Thesis: Hudson

CP violation in the Standard Model

- We can try to calculate EDMs from SM CKM phase





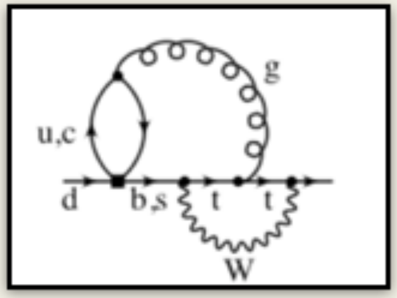
$$\mu = \frac{e}{2m_e}\frac{\alpha_{em}}{2\pi} \qquad d = 0$$

$$d_d \sim Im\left[V_{qd}V_{qd}^*\right] = 0$$

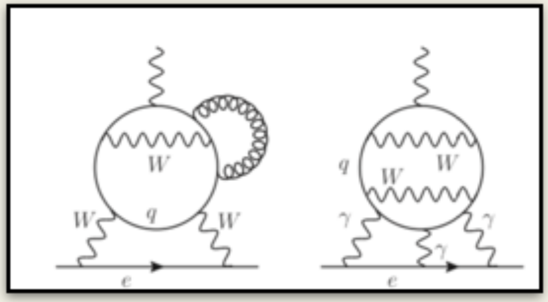
- **Vanishes at one-loop order!** Need to go to higher orders !

EDMs from the Standard Model

- At two loops: individual diagrams contribute but sum vanishes
- Quark EDMs induced at three loops



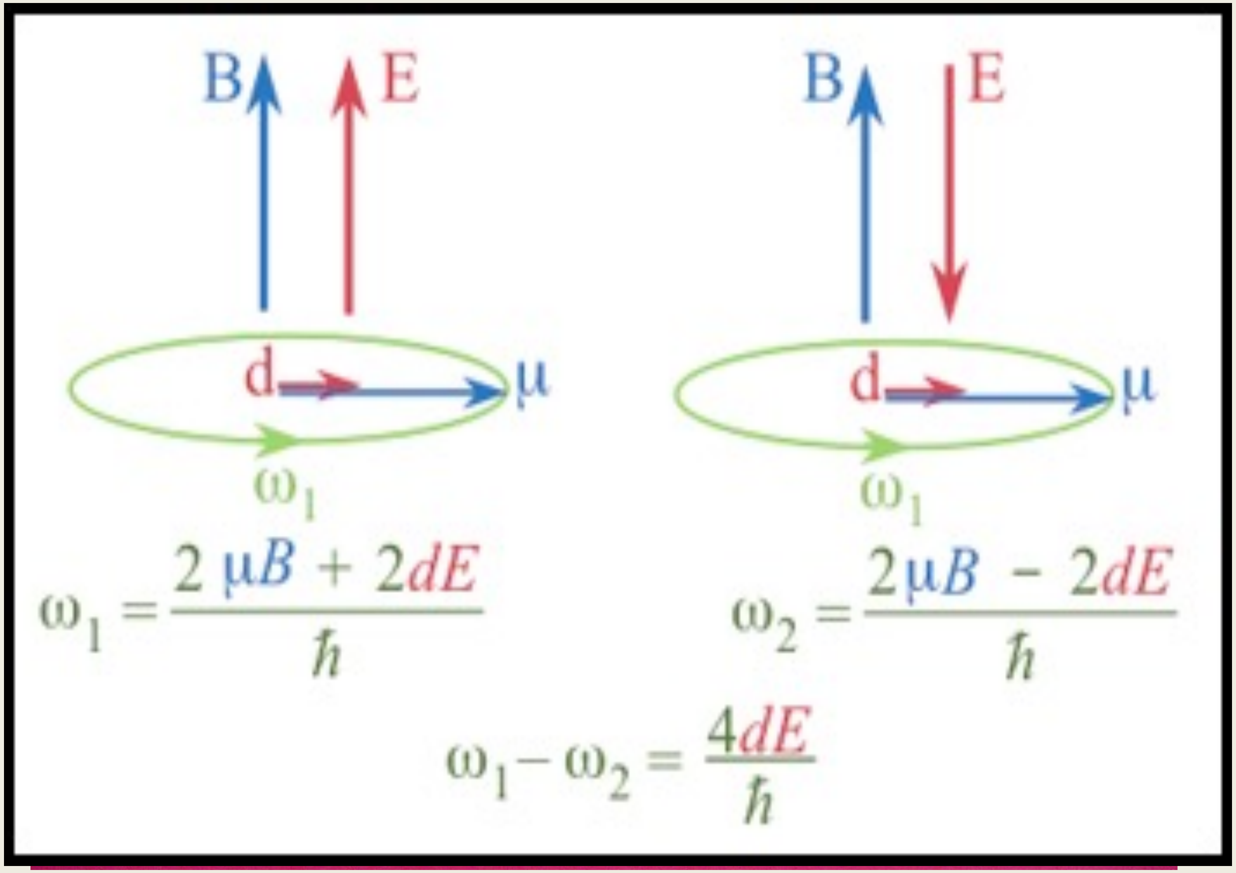
$$d_q \sim 10^{-34} e\,\text{cm}$$



- Electron EDM at 4 loops $\qquad d_e \sim 10^{-44} e\,\text{cm}$
- Compare with magnetic dipole moment: $\qquad \mu_e \sim 10^{-11} e\,\text{cm}$

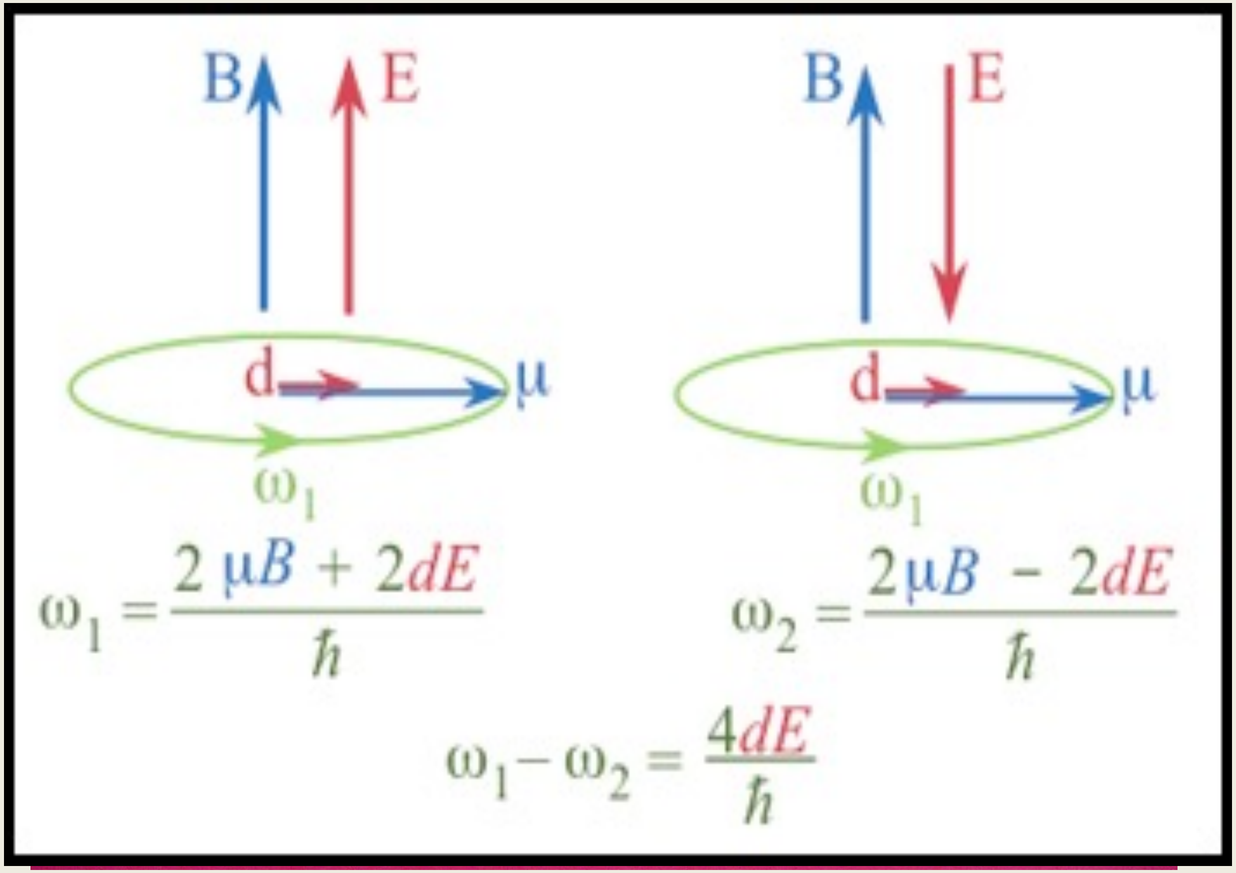
- Disclaimer 1: electron EDM can be a bit larger due to hadronic loops
- Disclaimer 2: EDMs of composite objects can be larger (still small)

The basic idea of measuring EDMs



- Note: the magnetic moment is more than 10 orders of magnitude larger…. Very good control of magnetic field required.

The basic idea of measuring EDMs

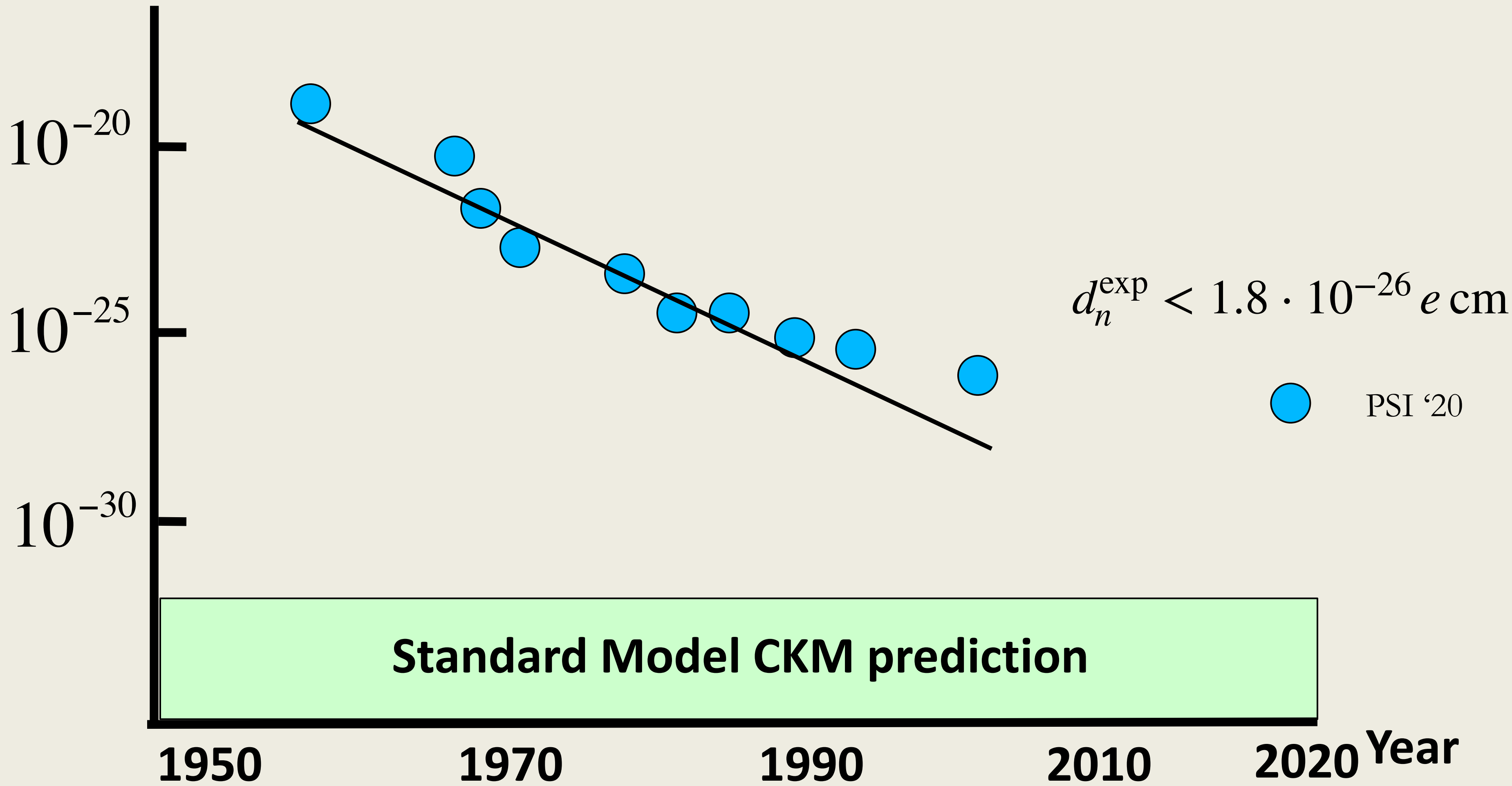


- Note $d = 10^{-28}\, e\, cm \qquad E = 100\ kV/cm$

$$\delta\omega \sim 10^{-7}\, rad/s \sim 1\ rad/year$$

Electric dipole moments and the CKM matrix

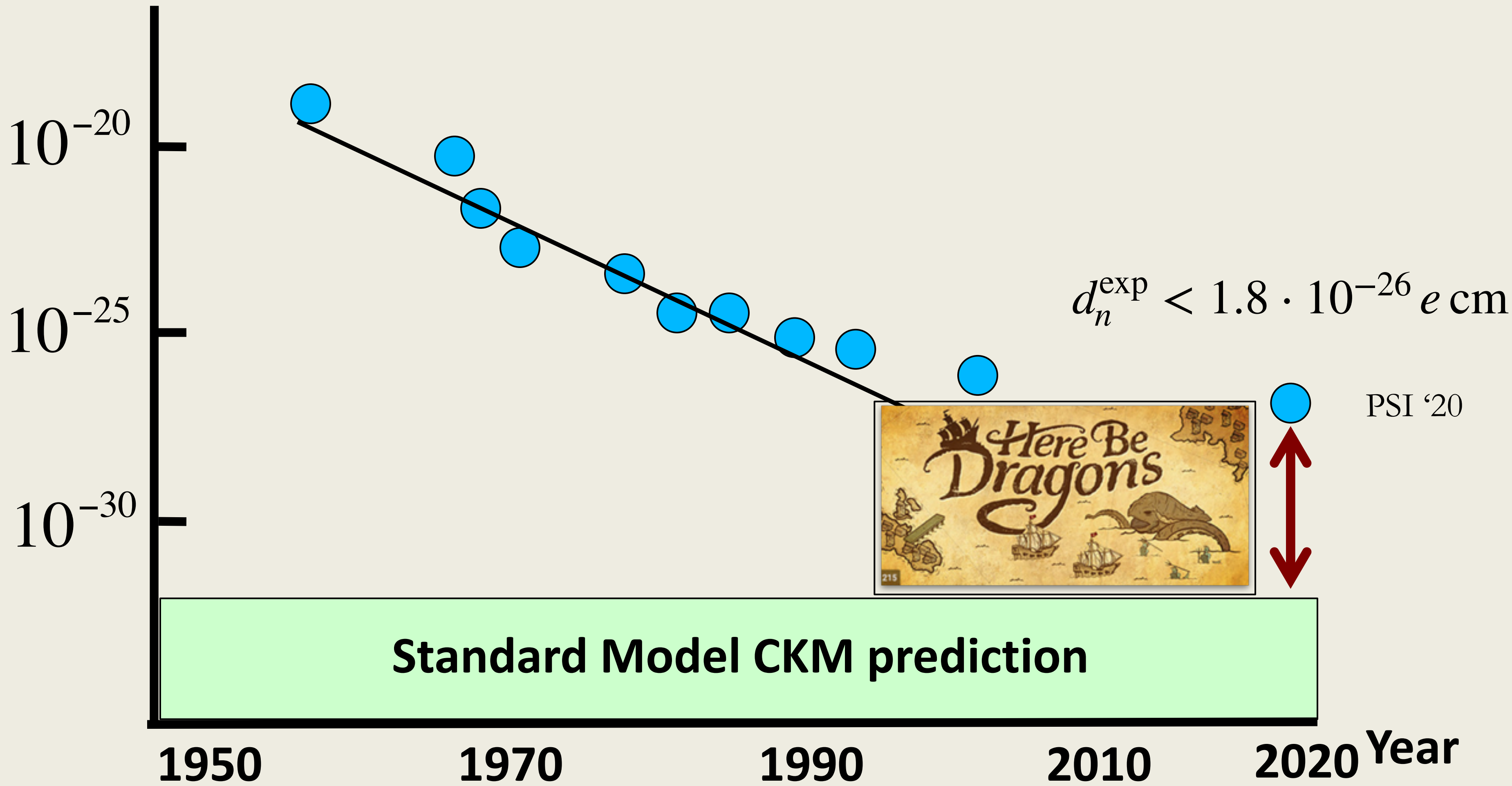
Limit on **neutron** EDM in e cm



More progress on electron EDM in recent times (factor 100 in 10 years)

Electric dipole moments and the CKM matrix

Limit on **neutron** EDM in e cm



Strong CP violation

- Just because CKM predictions are small, is not enough motivation

1. There is another source of CP violation in the Standard Model

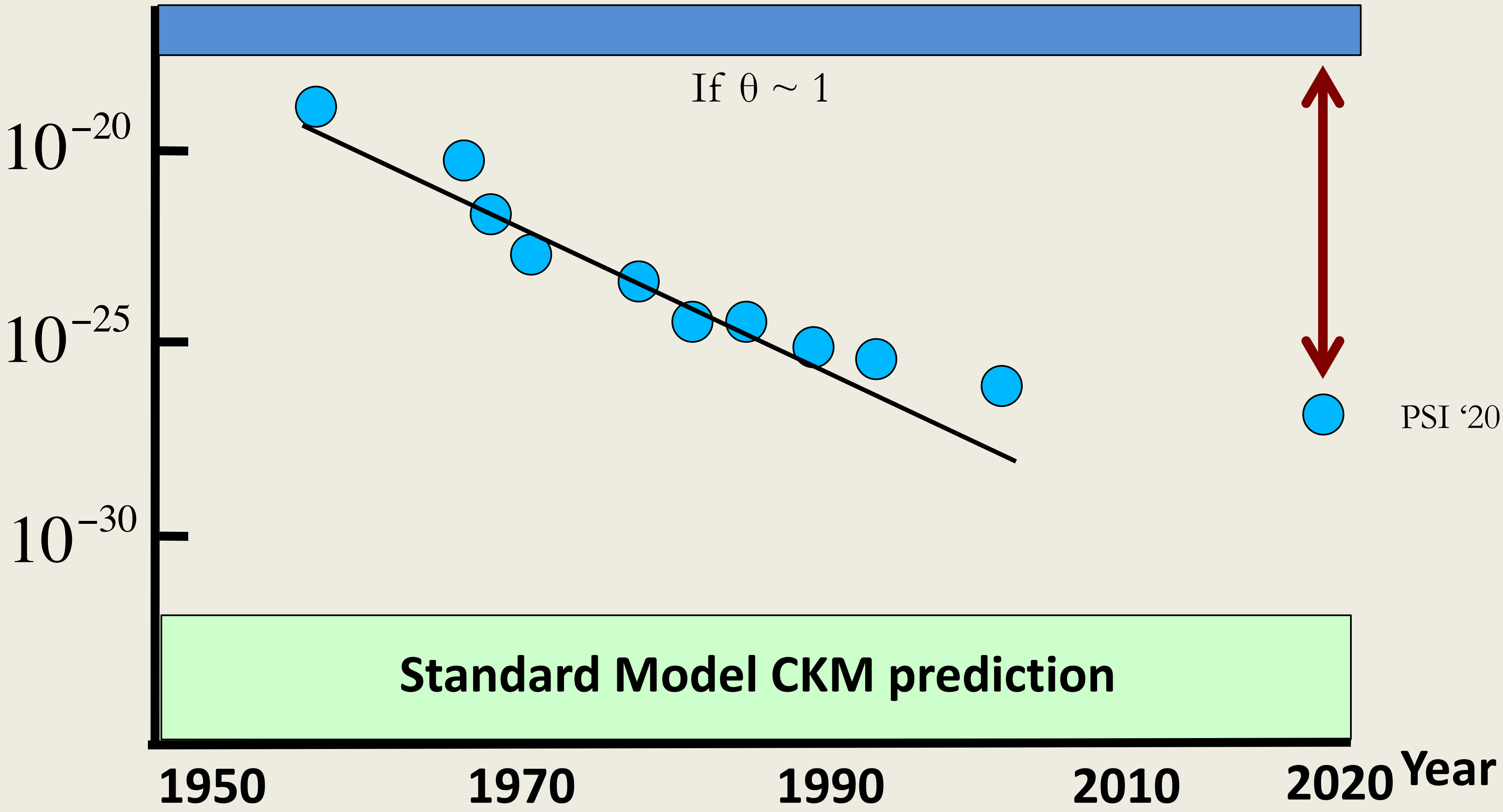
axial U(1) transformation

$$+\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} \longleftrightarrow -\left(\frac{m_u m_d}{m_u + m_d}\right)\theta\, \bar{q} i \gamma^5 q$$

Theta itself is unknown → **Have to measure it**

Strong CP violation

Limit on **neutron** EDM in e cm



Strong CP violation

- Just because CKM predictions are small, is IMO not enough motivation

1. **There is another source of CP violation in the Standard Model**

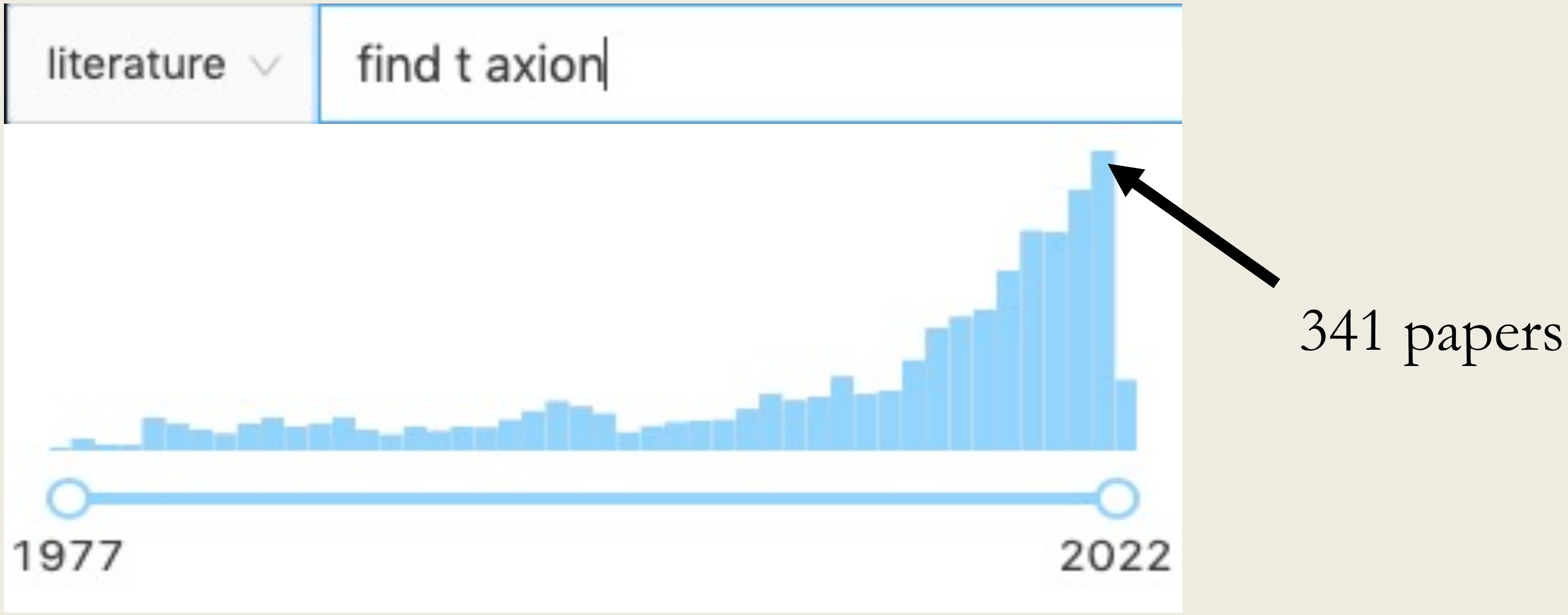
$$+\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} \quad \xleftrightarrow{\text{axial U(1) transformation}} \quad -\left(\frac{m_u m_d}{m_u + m_d}\right) \theta\, \bar{q} i \gamma^5 q$$

Theta itself is unknown → **Have to measure it** **$\theta < 10^{-10}$**

This is called the strong CP problem (driven by EDM searches)

Lead to a lot of theorizing: popular solutions are **axions** (could be dark matter)

Axions are hot



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Lead to a lot of theorizing: popular solutions are **axions**
(could be dark matter)

Very active experimental field

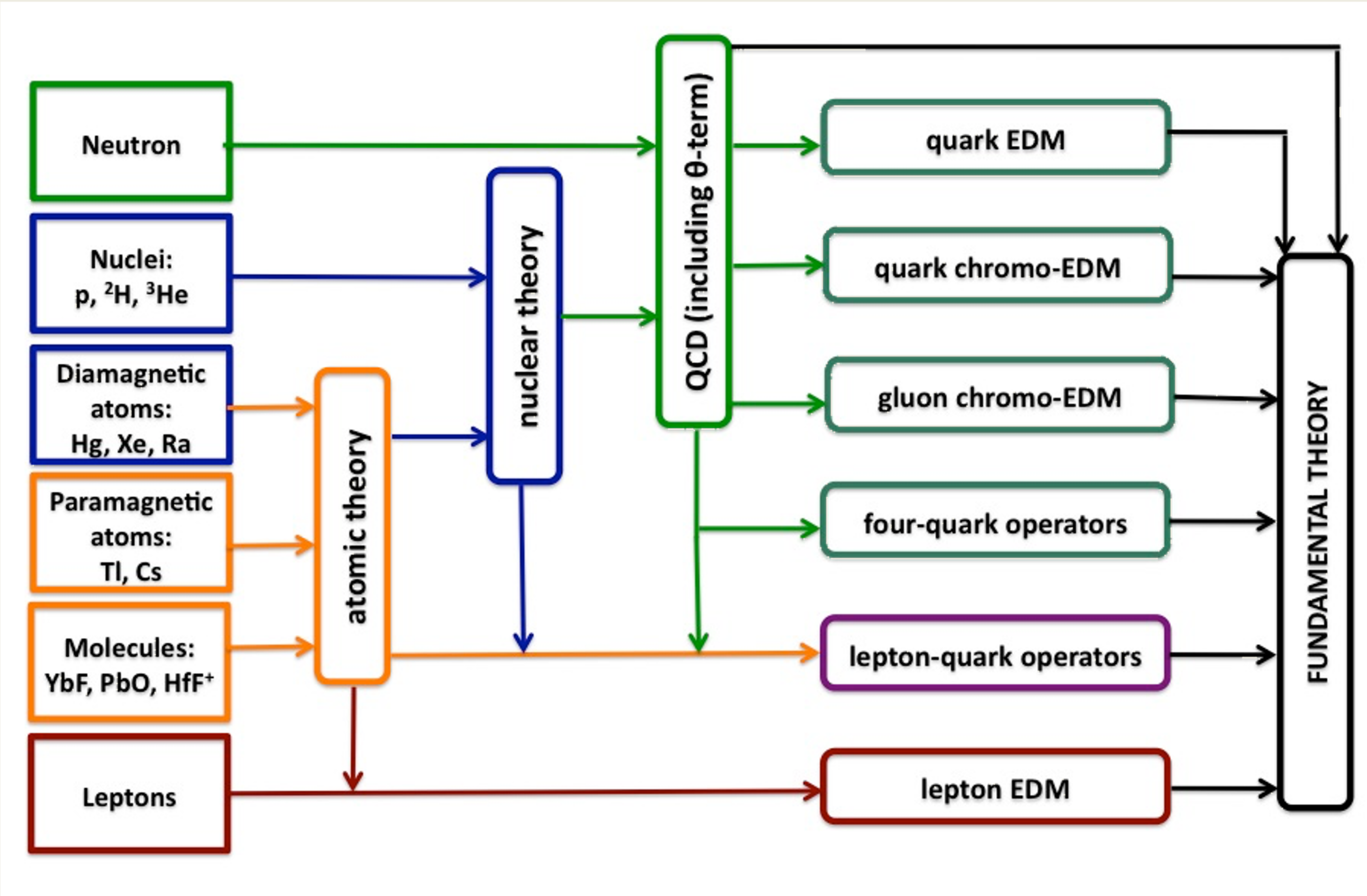
System	Group	Limit	C.L.	Value	Year
^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
ThO	ACME	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
HfF^+	Boulder	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017
n	Sussex-RAL-ILL	3.0×10^{-26}	90	$0.2(1.5)(0.7) \times 10^{-26}$	2006
^{129}Xe	UMich	4.8×10^{-27}	95	$0.26(2.3)(0.7) \times 10^{-27}$	2019
^{199}Hg	UWash	7.4×10^{-30}	95	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
^{225}Ra	Argonne	1.4×10^{-23}	95	$4(6.0)(0.2) \times 10^{-24}$	2016
muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

e (bracket marking the first four rows)

\+ new electron, muon, neutron, proton, Xe, Ra, Rn, **BaF**….. experiments

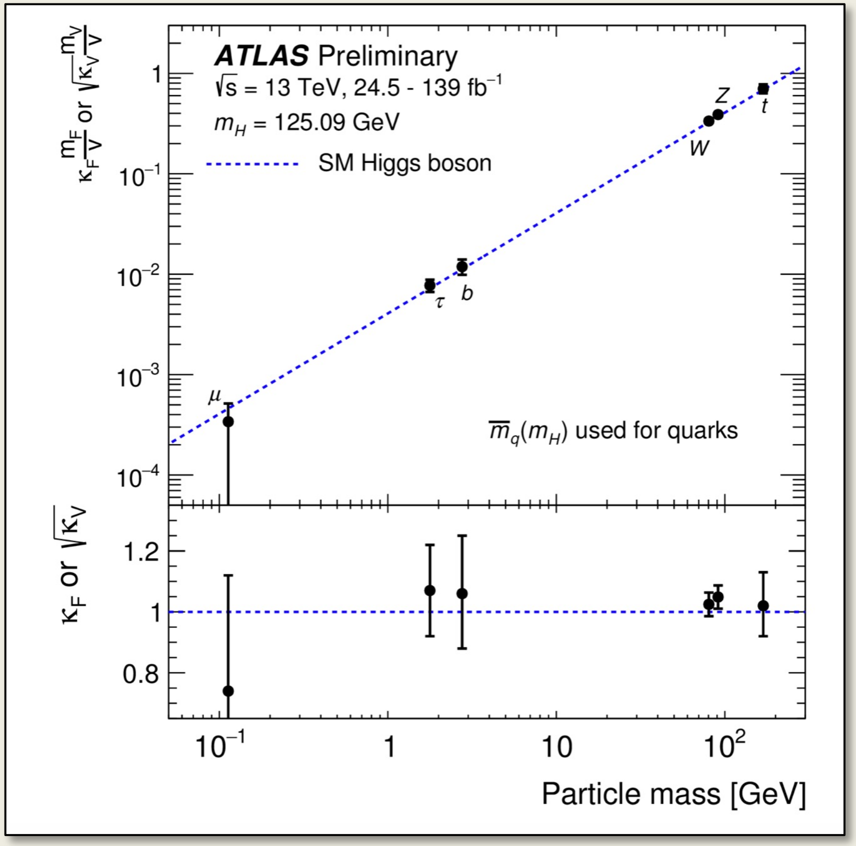
- **How do we interpret these limits ?**

The EDM metromap



New CP violation in the Higgs sector

- So far: Higgs properties **in agreement** with Standard Model



ATLAS summary plot

SM predictions

1. Higgs couples ~ to mass
2. Higgs is a scalar:
   No CP-violating couplings

Consequences of minimal Higgs sector

Needs to be tested !

- CP-violating Higgs interactions motivated by electroweak baryogenesis

Applications to electroweak baryogenesis

13.x billion years →

Generation of matter happens during EW phase transition

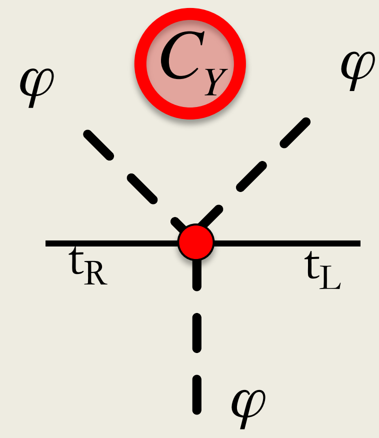
BSM physics to fulfill Sakharov conditions

1. A strong first-order EW phase transition (out-of-equilibrium)
2. Additional CP-violation (CKM phase + theta not enough)

An example of CP-odd Higgs violation

- **This talk:** interactions with Higgs that can violate CP
- Time constraints: a subset of dim-6 operators

$$L_{eff} = \sum C_\alpha O_\alpha + h.c. \qquad C_\alpha = c_\alpha + i\,\tilde{c}_\alpha \qquad C_\alpha \sim \frac{1}{\Lambda^2}$$



Example: dim-6 coupling between Higgs and quarks

$$C_Y\, y_t \bar{t}_L t_R \tilde{\varphi} (\varphi^\dagger \varphi) + h.c. \longrightarrow L = C_Y\, m_t \bar{t}_L t_R (1 + 3vh + 3h^2 + \cdots) + h.c.$$

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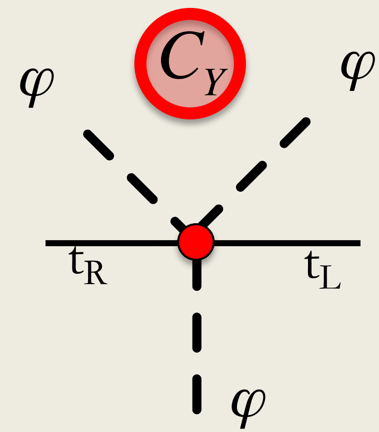

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1. Yukawa coupling no longer aligned to fermion mass
2. New source of **CP violation**
3. Multi-Higgs interactions affect e.g. di-Higgs production

- Rather general consequences of more complicated Higgs sector

An example of CP-odd Higgs violation

- **This talk:** interactions with Higgs that can violate CP
- Time constraints: a subset of dim-6 operators

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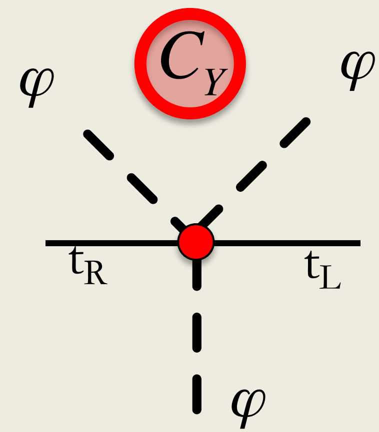
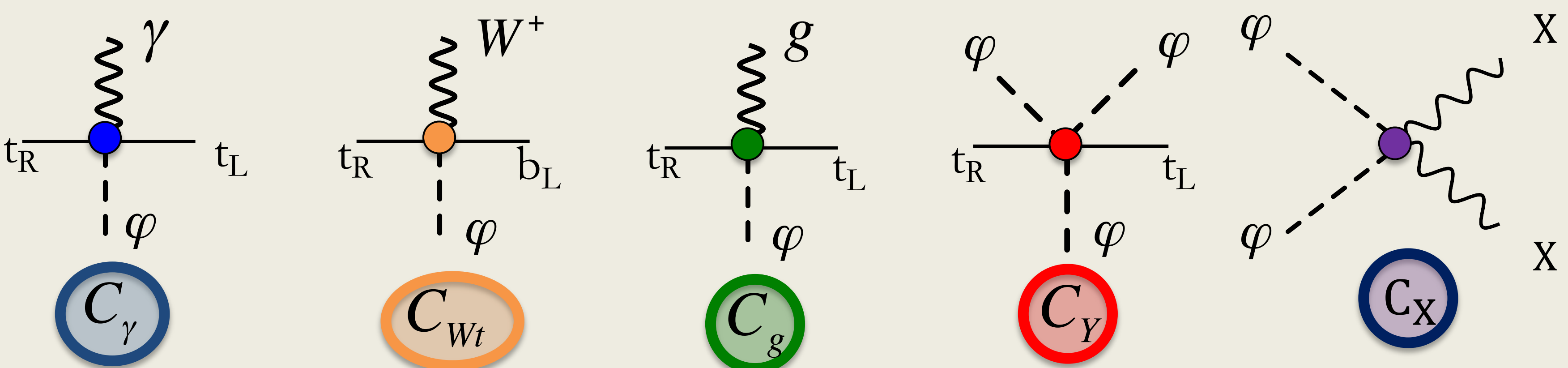


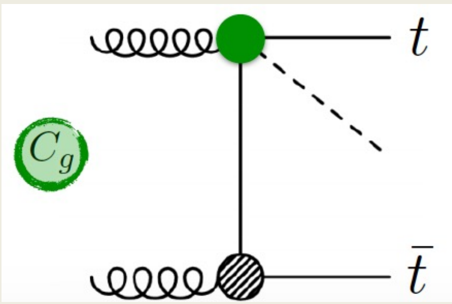
- Just one example: several other operators appear

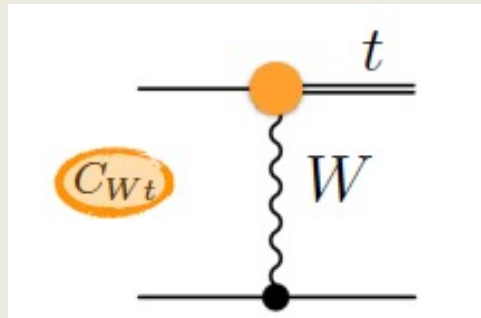


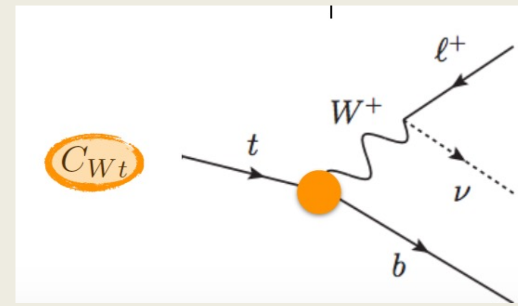
Collider searches

Degrande et al ’10 - ’13
Buckley et al ‘14 ‘15
Willenbrock et al ‘13’14
Maltoni et al 14’ 15’ ’16
Elias-Miro et al ‘13
JdV et al ‘16

- These operators modify all kinds of LHC processes
- Lots of papers + NLO QCD corrections etc.



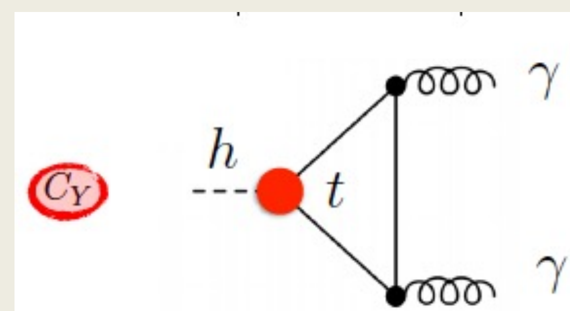




Top-Antitop-Higgs production

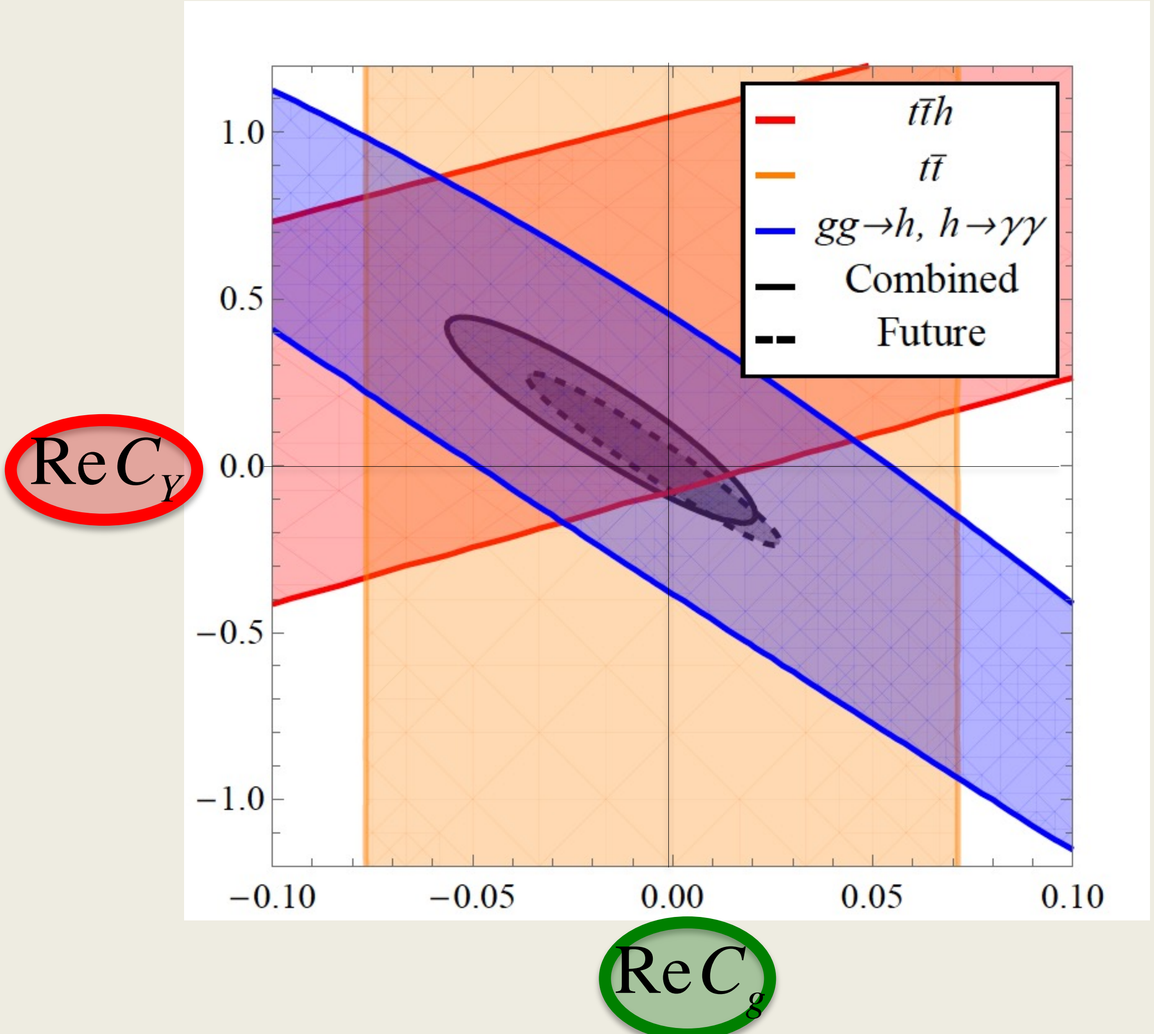
Single-top production and top decay

- But also just higgs production/decay via **loop processes**



Connection to data

Cirigliano, Dekens, JdV, Mereghetti '16



Brown et al'19
Hartland et al '19 ,
Brivio et al '19,
Ellis et al '18 , …..

- Typical constraints: $|v^2\,\mathrm{Re}(C)| < 0.05\text{-}0.3$ → $\Lambda \geq 1000 - 2000\ GeV$
- More recent analyses by other groups with more processes/operators
- **Focus on CP-even parts.** CP-odd parts via (dim-6)^2 → weaker constraints

What about CP violation ?

Demartin et al ’15, Mileo et al ’16

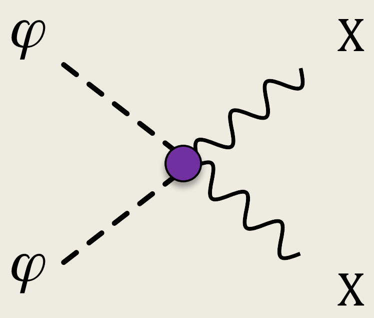
- Imaginary part probed @ LHC, e.g. ttH **triple or quadrupole products**

$$pp \to t\,(\to b l^+ \nu_l) + \bar{t}\,(\to \bar{b} l^- \bar{\nu}_l) + h$$

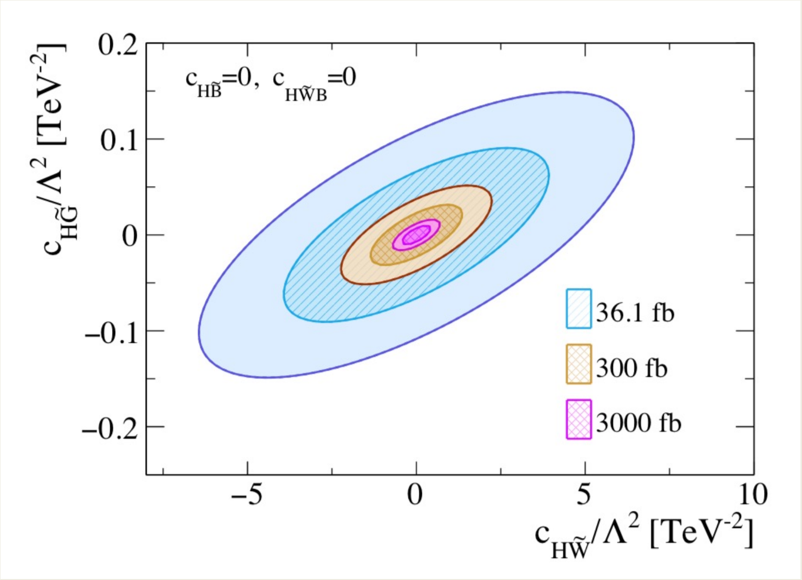
$$\varphi \sim ((\vec{p}_{l+} \times \vec{p}_{l-}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}))\,(\vec{p}_{l+} - \vec{p}_{l-}) \cdot (\vec{p}_b + \vec{p}_{\bar{b}})$$

- CP-violation in h+2 jets via Higgs-gauge couplings
- Current constraints not too strong but better prospects for HI-LHC

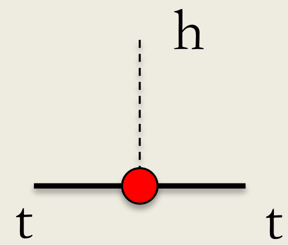
$$v^2 \text{ Im } C_Y < 0.2$$



Bernlochner et al’ 18
JdV et al PRL ‘19



How can EDMs help ?



$$C_Y \; y_t \overline{t}_L t_R \tilde{\varphi} \left(\varphi^\dagger \varphi \right) + h.c.$$

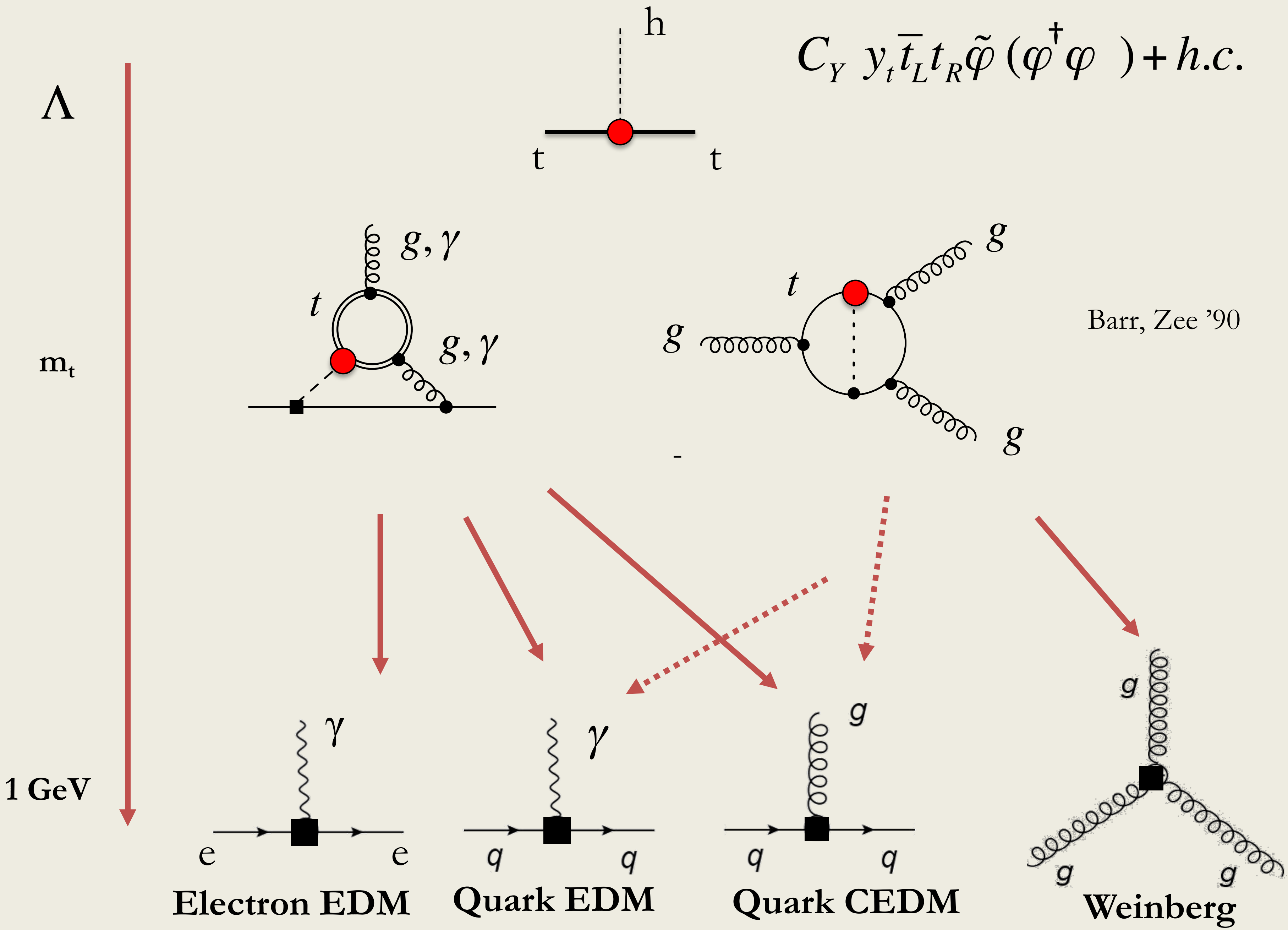
Λ

m_t

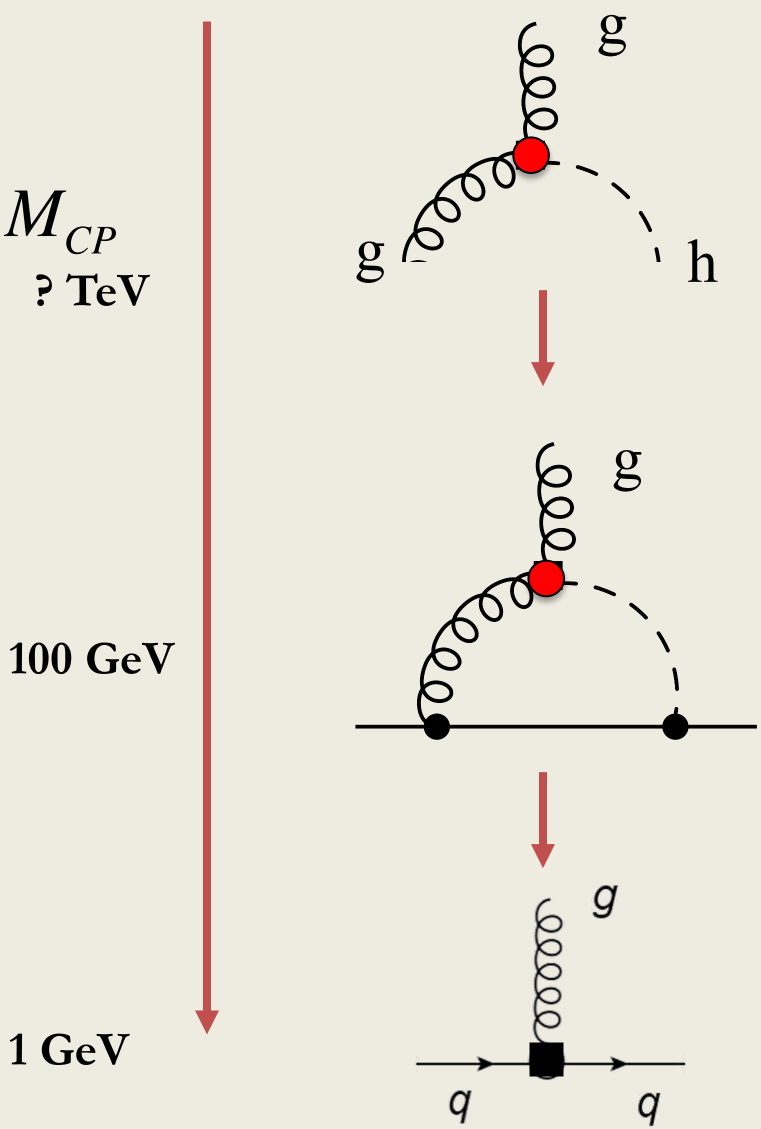
1 GeV

How can EDMs help ?

$$C_Y \; y_t \bar{t}_L t_R \tilde{\varphi} (\varphi^\dagger \varphi) + h.c.$$



Another example



Search at the same time at LHC.

One example: $\theta' H^2 G\tilde{G}$

a) Probed at LHC (affects gluon fusion)

b) Induces quark (C)EDM + Weinberg operator

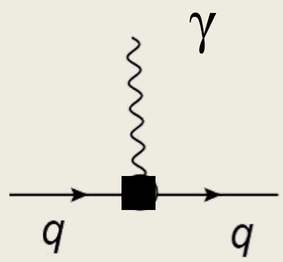
Similar for **Higgs-photon/Z/W** operators

Plus others… But when the dust settles…..

Few GeV

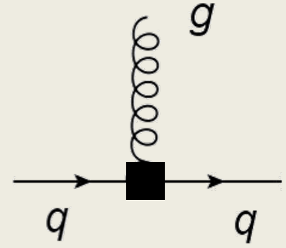
QCD
(θ-term)

+



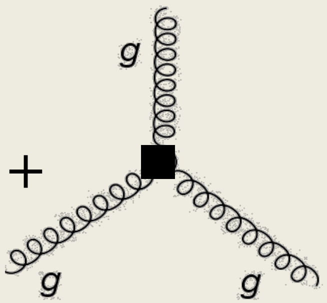
Quark EDM

+



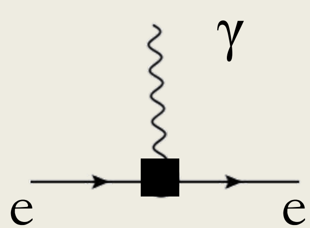
Quark C-EDM

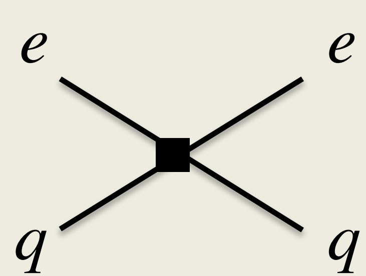
+



Gluon C-EDM

(semi-)leptonic interactions





Paramagnetic systems

e

System	Group	Limit	C.L.	Value	Year
^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
ThO	ACME	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
HfF^{+}	Boulder	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017

- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

Paramagnetic systems

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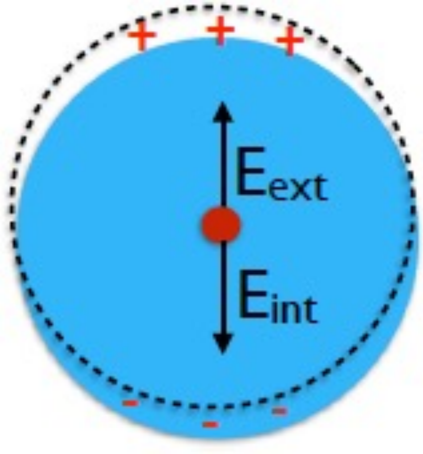
- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

Schiff Theorem: EDMs of charged constituents are screened in a neutral atom Schiff, '63



- Assumption : **non-relativistic constituents**
- **Invalid in heavy atoms/molecules**

$$d_A(d_e) = K_A d_e \qquad K_A \propto Z^3 \alpha_{em}^2$$

Sandars '65

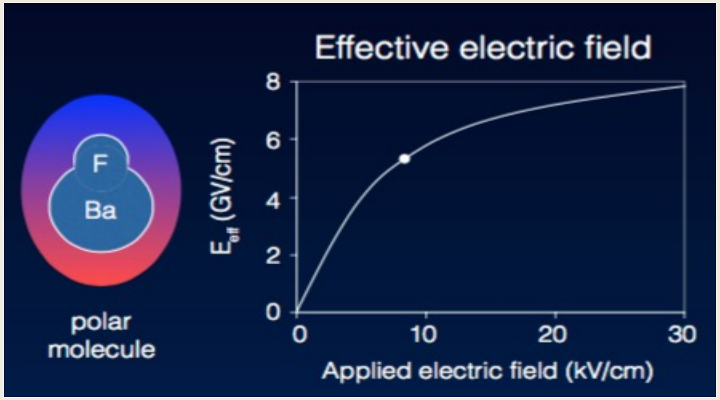
Probing the leptonic interactions

Bound on atomic Tl EDM : $d_{^{205}Tl} < 9 \cdot 10^{-25}\ e\ cm$ Regan et al '02

$d_A(d_e) = K_A d_e$ $K_{Tl} = -(570 \pm 20)$ **Strong enhancement!**

$\longrightarrow$ $d_e < 1.6 \cdot 10^{-27}\ e\ cm$

Probing the leptonic interactions

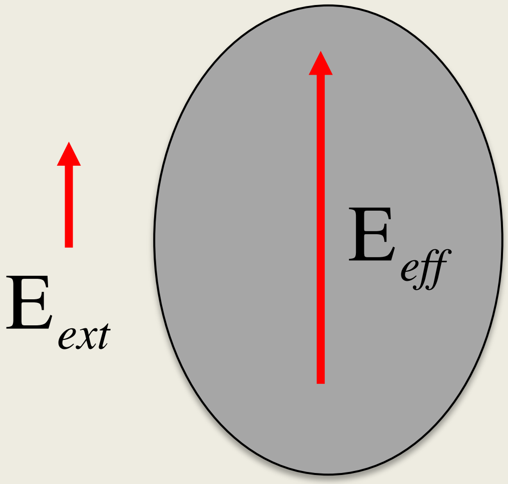


Polar molecules:

Convert small external to **huge** internal E field

$$\mathrm{E}_{eff} \propto 10^6 E_{ext}$$

Requires high-accuracy electronic structure computations



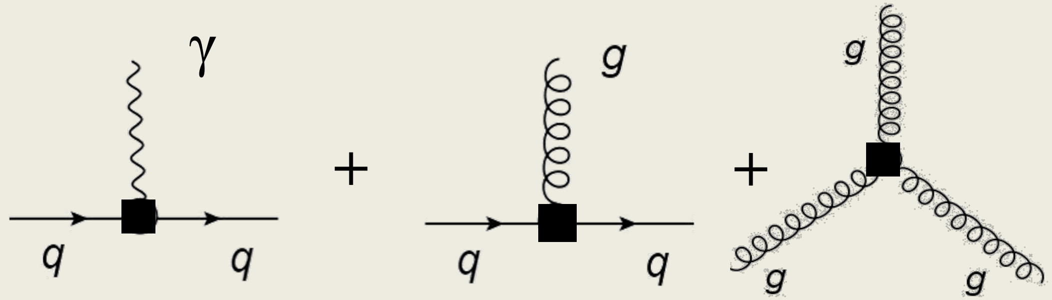
$$\Delta E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\ cm} \right)$$

$$d_e < 1.4 \cdot 10^{-29}\ e\ cm$$ Andreev et al ’18

Onwards to hadronic CPV

Few GeV

QCD
(θ-term) + Quark EDM + Quark chromo-EDM + Weinberg operator



Quark EDM

Quark chromo-
EDM

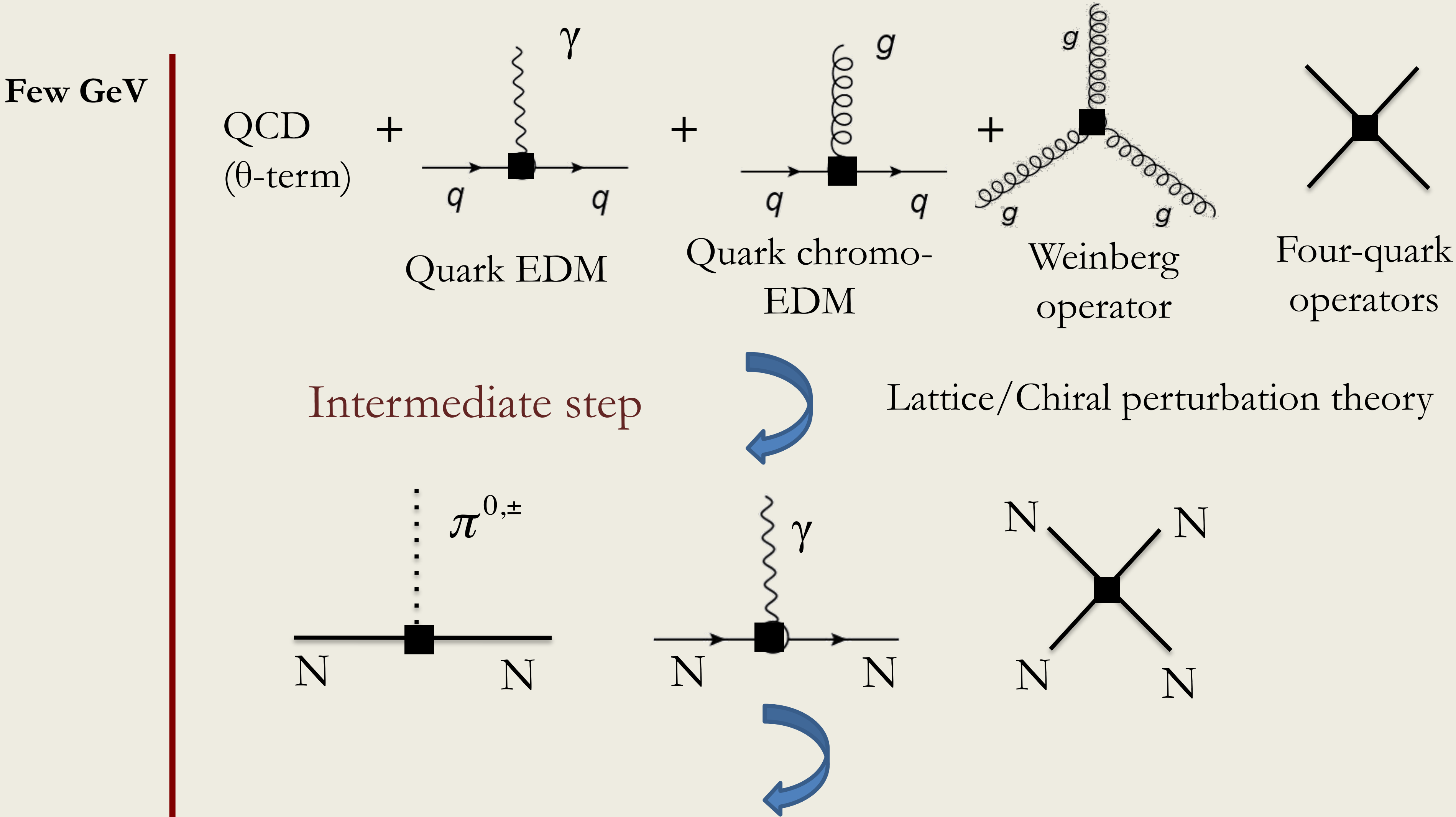
Weinberg
operator

Hadronic/Nuclear CP-violation

Theoretically more difficult

Goal: **Electric dipole moments of nucleons, nuclei, and diamagnetic systems**

Onwards to hadronic CPV



Goal: **Electric dipole moments of nucleons, nuclei, and diamagnetic atoms**

An ultrashort intro to Chiral EFT

- Use the symmetries of QCD to obtain **chiral Lagrangian**

$$L_{QCD} \rightarrow L_{chiPT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots$$

- Quark masses = 0 → $SU(2)_L x SU(2)_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)
  - Explicit breaking (quark mass) → pion mass

An ultrashort intro to Chiral EFT

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  - Explicit breaking (quark mass) → pion mass

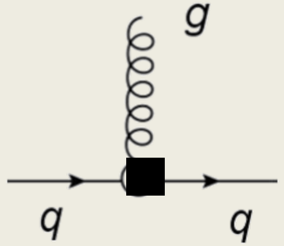
- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\quad \Lambda_\chi \cong 1\, GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)

- **Extended to include CP violation** JdV et al '12, Bsaisou et al '14

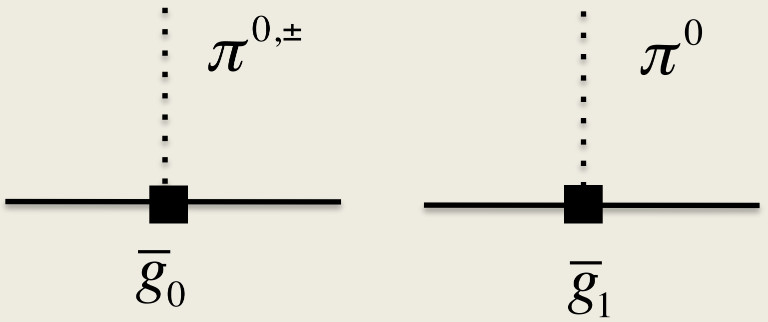
Weinberg, Gasser, Leutwyler, and many many others

Hadronic CP violation

- **Example: quark chromo-EDM**



- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**



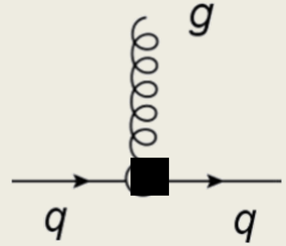
$$L = g_0 \, \bar{N} \pi \cdot \boldsymbol{\tau} N + g_1 \, \bar{N} \pi^0 N$$

- Hadronic LECs poorly known (50-75% uncertainty) → lattice in Progress

Example: $\bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$

Hadronic CP violation

- **Example: quark chromo-EDM**



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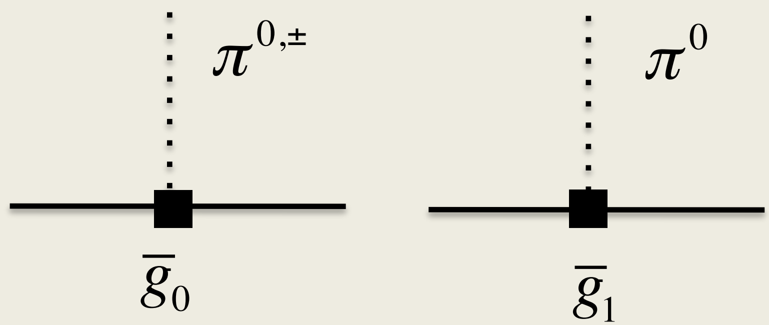
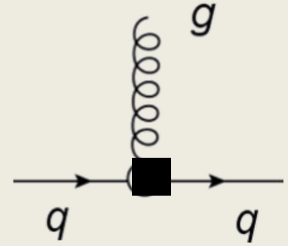


$$L = g_0\, \bar{N}\pi\cdot\boldsymbol{\tau} N + g_1\, \bar{N}\pi^0 N$$

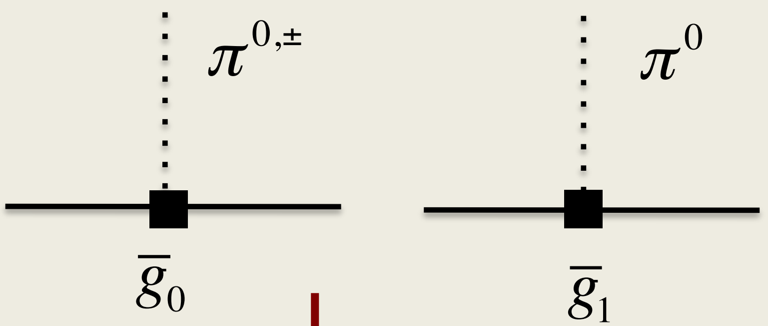
- Ratios are a bit better known

	Theta term	Quark CEDMs	Four-quark operators	Quark EDM and Weinberg
$\dfrac{\bar{g}_1}{\bar{g}_0}$	–0.2	≈ 1	+50	Both couplings are suppressed !

Hadronic CP violation

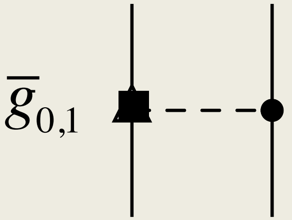


- **Example: quark chromo-EDM**
- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**

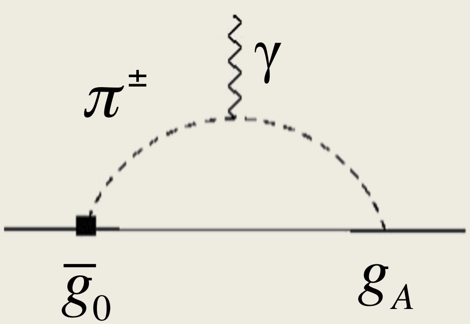


Tree

CP-odd nuclear force

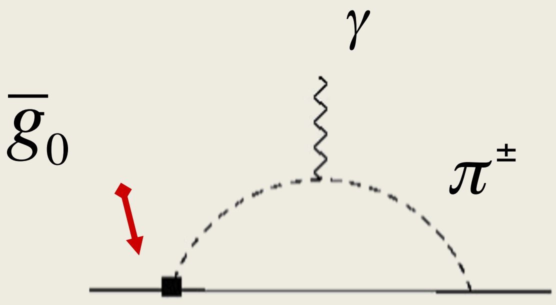


1-Loop
Neutron EDM

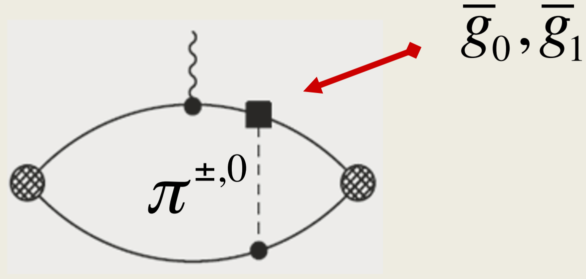


Additional uncertainty from short-distance contributions

More than one nucleon



Nucleon EDM



Nuclear EDM

- New contribution from CP-odd pion exchange: **no loop** suppression

$$d_A = < \Psi_A \| \vec{J}_{\not{CP}} \| \Psi_A > \; + \; 2 < \Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A >$$

$$(E - H_{PT}) | \Psi_A > = 0$$
$$(E - H_{PT}) | \tilde{\Psi}_A > = V_{\not{CP}} | \Psi_A >$$

- **Pion-exchange contribution can be larger than nucleon EDMs !**
- Chiral calculation of wave functions + CPV potential and currents

The chiral filter

Khriplovich/Korkin '00
Bsaisou et al '14

- Example: the simplest nucleus

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

`	**Theta term**	**Quark CEDMs**	**Four-quark operator**	**Quark EDM and Weinberg**
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio suffers from hadronic (not nuclear!) uncertainties **(need lattice)**
- EDM ratio hint towards **underlying CP-odd operator**!
- **EDMs of nuclei can be enhanced !**

Onwards to heavy systems

Graner et al, '16

Strongest bound on atomic EDM: $d_{^{199}Hg} < 8.7 \cdot 10^{-30}\ e\,cm$

New measurements expected: Ra , Xe, ….

Schiff Theorem: EDM of nucleus is screened by electron cloud if:

1. Non-relativistic kinematics
2. Point particles

Schiff, '63

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Schiff, '63

Screening incomplete: nuclear finite size (Schiff moment **S**)

$$S \equiv \left\langle \Psi_0 \middle| \hat{S}_0 \middle| \Psi_0 \right\rangle \cong \sum_{i \neq 0} \frac{\left\langle \Psi_0 \middle| \hat{S}_0 \middle| \Psi_i \right\rangle \left\langle \Psi_i \middle| V_{\not{PT}} \middle| \Psi_0 \right\rangle}{E_0 - E_i}$$

Schiff operator $S_0 \sim \sum_i \left(r_i^3 - \frac{5}{3} r_{ch}^2 r_i \right) Y_0^1$

Onwards to heavy systems

Graner et al, '16

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Schiff Theorem: EDM of nucleus is screened by electron cloud if:

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Schiff, '63

Screening incomplete: nuclear finite size (Schiff moment **S**)

Typical suppression: $$\frac{d_{Atom}}{d_{nucleus}} \propto 10 Z^2 \left(\frac{R_N}{R_A}\right)^2 \approx 10^{-3}$$

- **Atomic** part well under control

$$d_{^{199}Hg} = (2.8 \pm 0.6) \cdot 10^{-4}\ S_{Hg}\ e\ fm^2$$

Dzuba et al, '02, '09

Sing et al, '15
Jung, Fleig '18

EFT and many-body problems

- Need to calculate Schiff Moment (or MQM) of Hg, Ra, Xe….
- **Issue:** does chiral power counting hold ? Do pions dominate ?
- Say we assume so:

$$S = (a_0 \bar{g}_0 + a_1 \bar{g}_1)\, e\, fm^3$$

	a_0 range	**a_1 range**
^{199}Hg	0.3±0.4	0.45±0.7
^{225}Ra	2.5±7.5	65±40

Flambaum, de Jesus, Engel, Dobaczewski,….

- Uncertainties make interpretation more difficult
- **Great challenge: improved nuclear structure computations**

table from review: Engel, Ramsey-Musolf, van Kolck, '13 + updates e.g. Engel et al PRL '18

Some new ideas

PHYSICAL REVIEW LETTERS **121**, 232501 (2018)

Correlating Schiff Moments in the Light Actinides with Octupole Moments

Jacek Dobaczewski,[1,2,3,4] Jonathan Engel,[5] Markus Kortelainen,[2,4] and Pierre Becker[1]

- In nuclei like ^{225}Ra there is a low-lying state with opposite parity

$$S \cong -2 \frac{\langle \Psi_0 | \hat{S}_0 | \bar{\Psi}_0 \rangle \langle \bar{\Psi}_0 | V_{\cancel{PT}} | \Psi_0 \rangle}{\Delta E}$$

- Schiff operator closely related to the **octupole charge operator**

$$\hat{Q}_0^3 \sim e \sum_i \left(r_i^3 \right) Y_0^3 \longrightarrow \langle \hat{Q}_0^3 \rangle = (940 \pm 30) e\ fm^3$$

Gaffney et al, Nature '13

Note: measurement is for ^{224}Ra

Some new ideas

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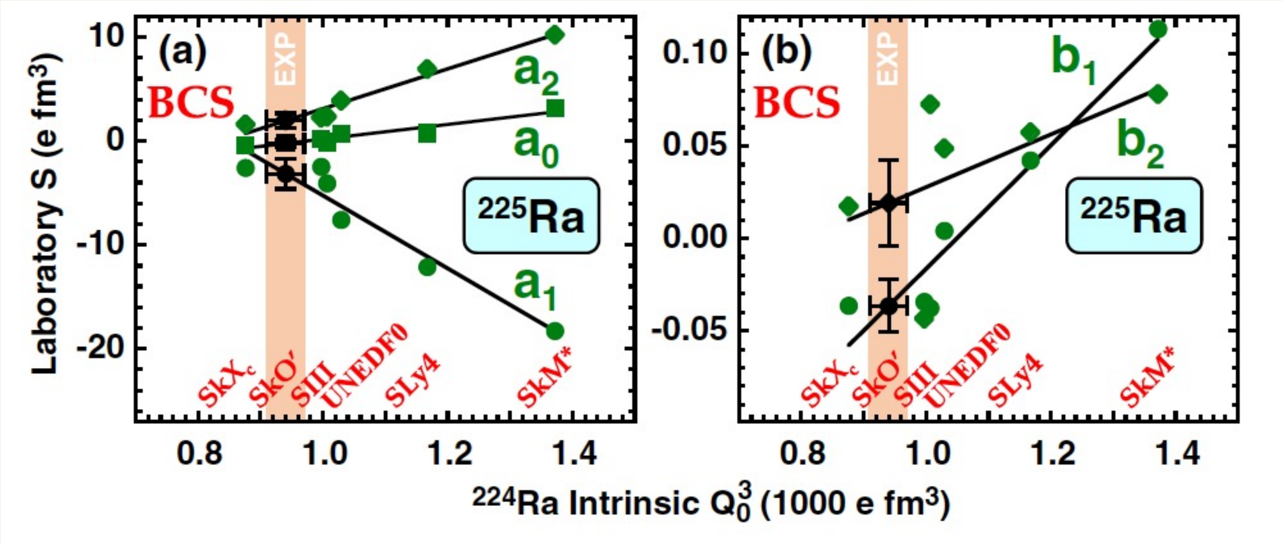
Jacek Dobaczewski,[1,2,3,4] Jonathan Engel,[5] Markus Kortelainen,[2,4] and Pierre Becker[1]

- CPV potential from EFT

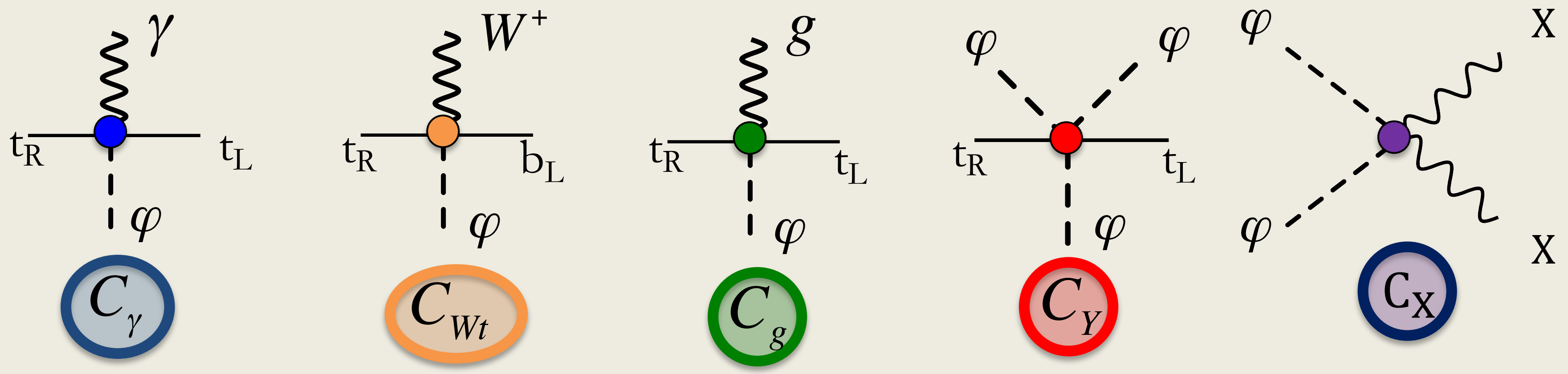
$$S = g(a_0\bar{g}_0 + a_1\bar{g}_1) + b_1\bar{C}_1 + b_2\bar{C}_2$$

- Observe relation between a_i , b_i and octupole moment

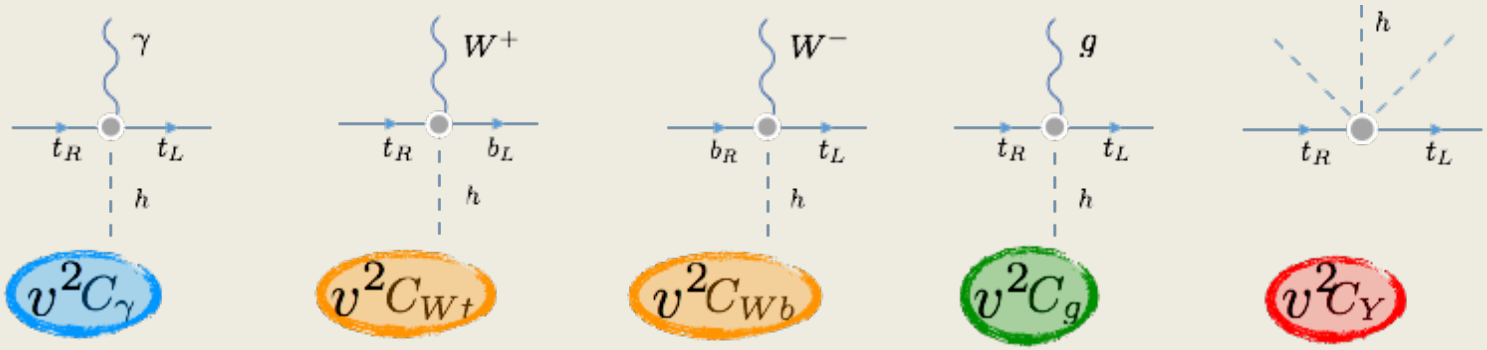


Now remember where we started

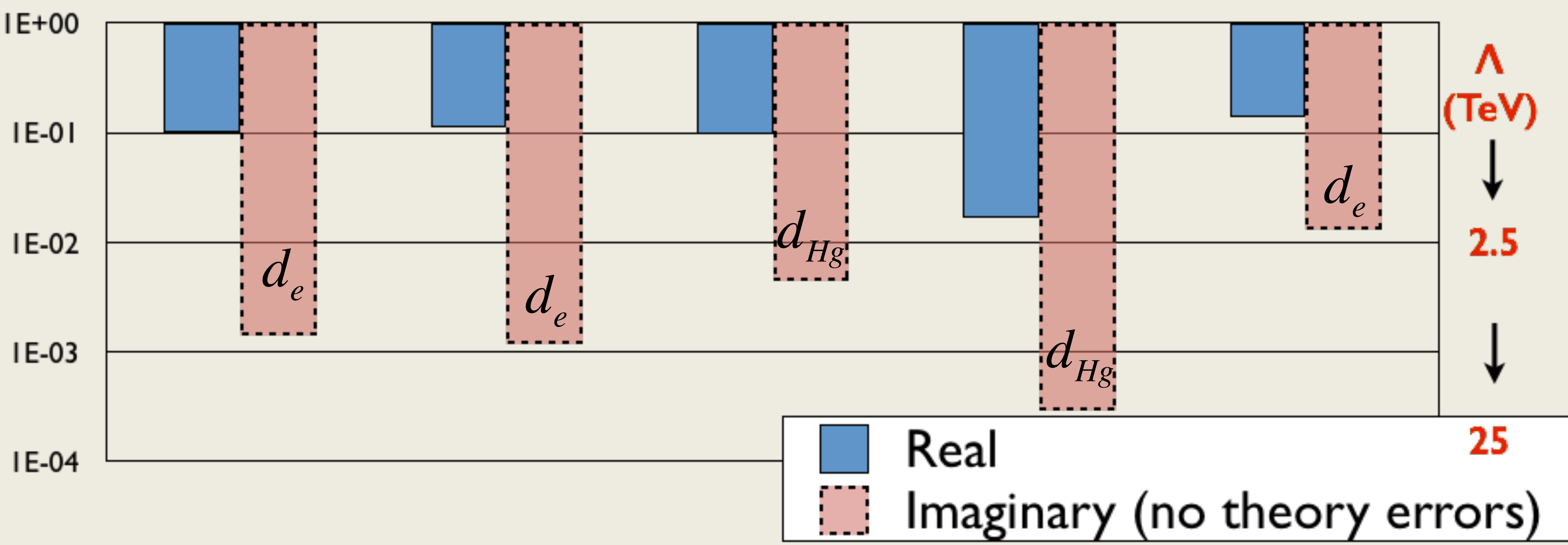
We now have a connection between Higgs CPV and EDMs of nucleons, nuclei, atoms, and molecules



How much room for CPV is left ?



$$C_\alpha \sim \frac{1}{\Lambda^2}$$



- EDMs are very constraining. Bounds dominated by d_{Hg} and d_e
- **Several caveats**

Strategy for setting limits

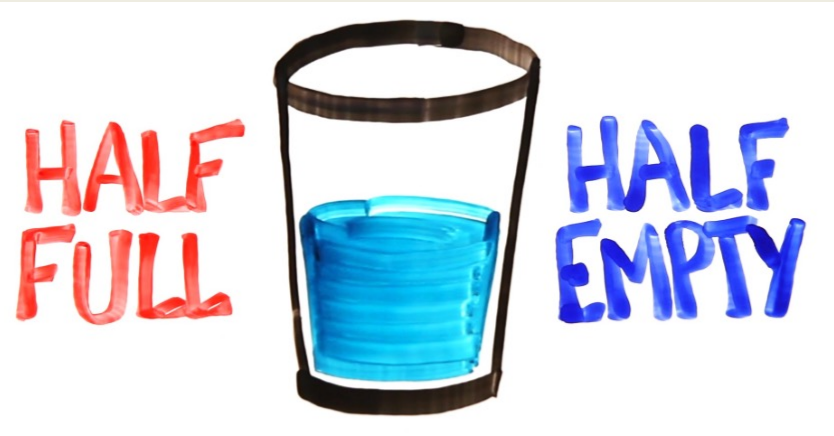
Study impact of **theory uncertainties** in the hadronic/nuclear EDMs.

Two extreme strategies

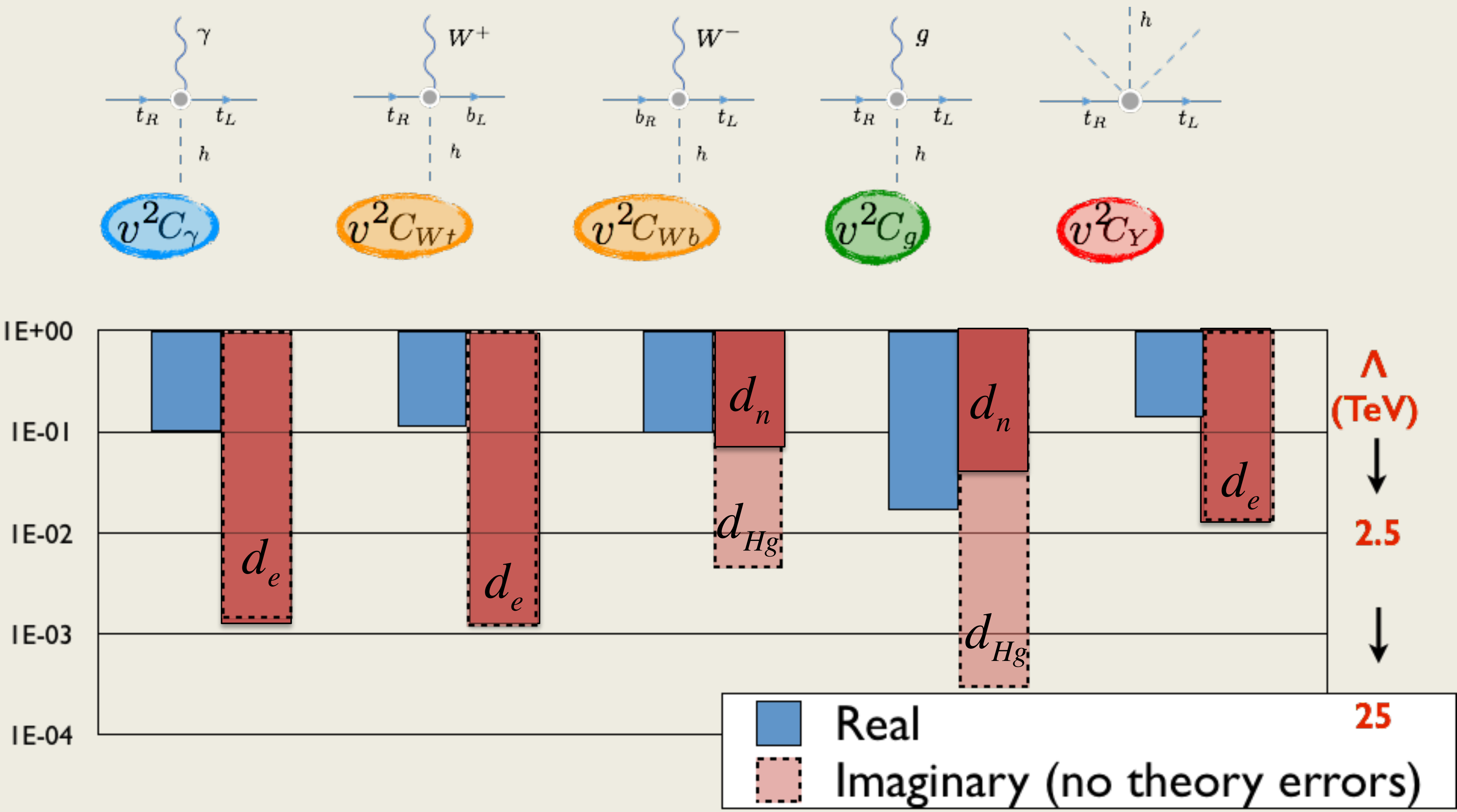
1. **Central:** use **central** value matrix elements (most common)

1. **RFit** ("Range-Fit"): vary matrix elements in their allowed ranges to minimize chi-squared (=**most conservative** bounds)

Strategy copied from CKMfitter group '04



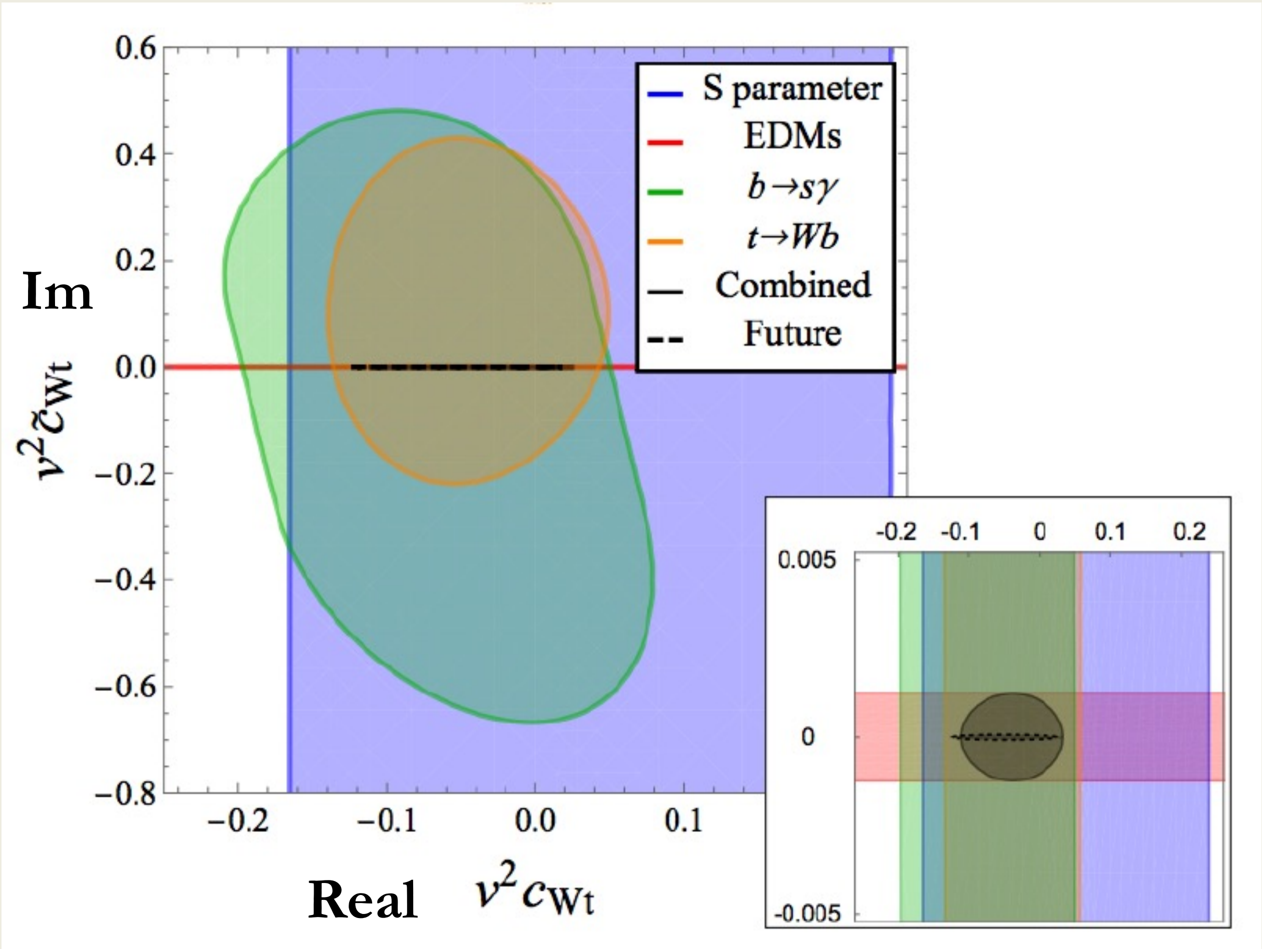
How much room for CPV is left ?



- **Nuclear and hadronic theory needs to improve**

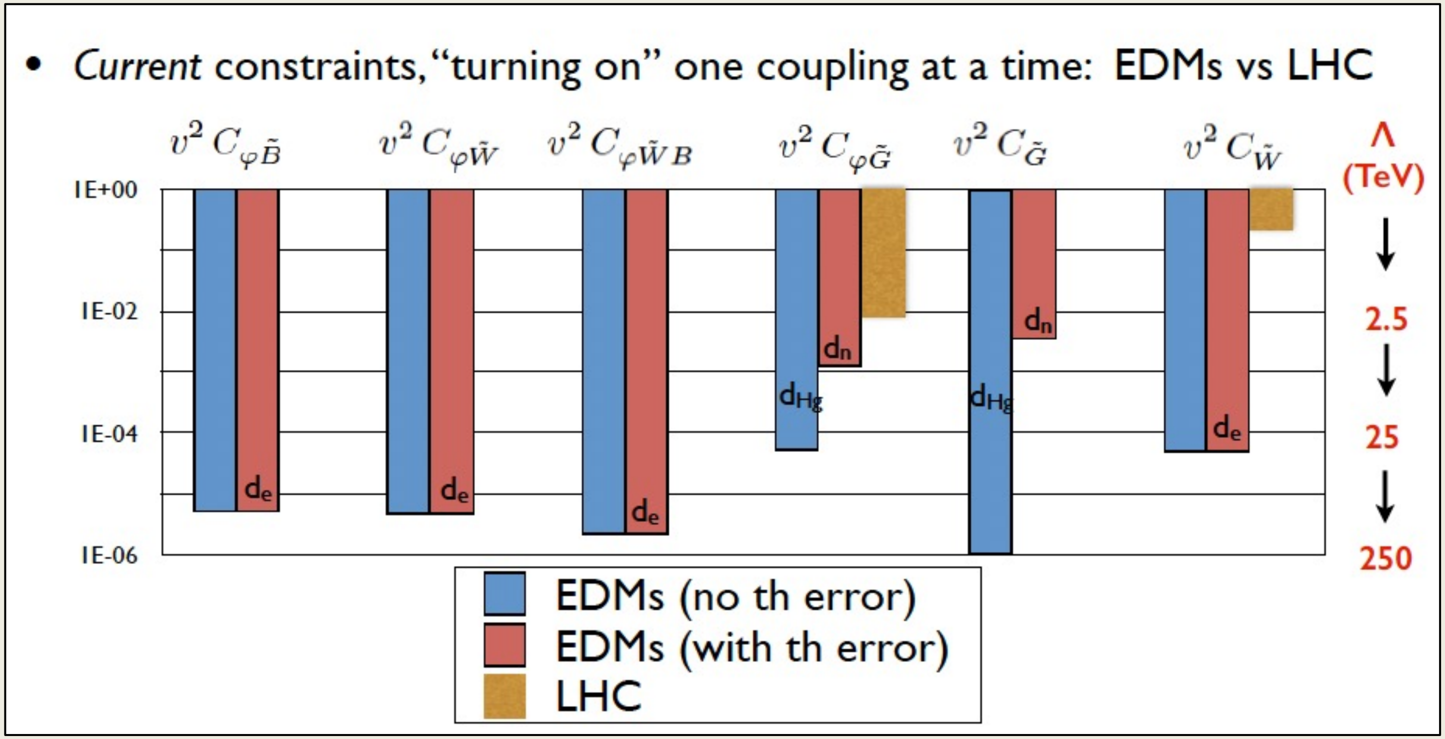
CP-even versus CP-odd

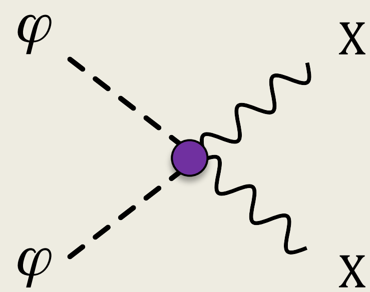
JdV et al ’16



- **CP-even** Higgs couplings dominated by **LHC** measurements
- **CP-odd** Higgs couplings dominated by **low-energy** measurements
- **Very complementary experiments**

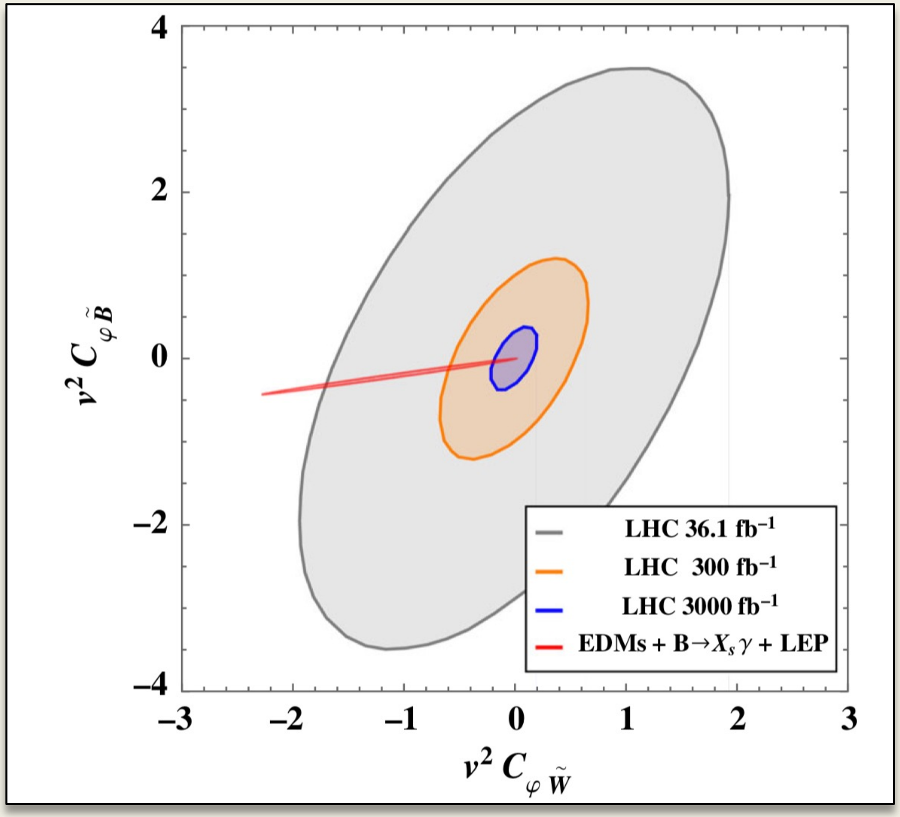
Low-energy constraints are stringent





- EDM constraints are very stringent for single couplings
- **But EDMs only probe several direction in parameter space**

Teamwork



Cirigliano et al PRL ‘19

HL-LHC projections from Bernlochner et al ‘18

- Low-energy limits avoided in global fits (free directions)
- **Future of BSM searches: inclusive low- and high-energy probes**

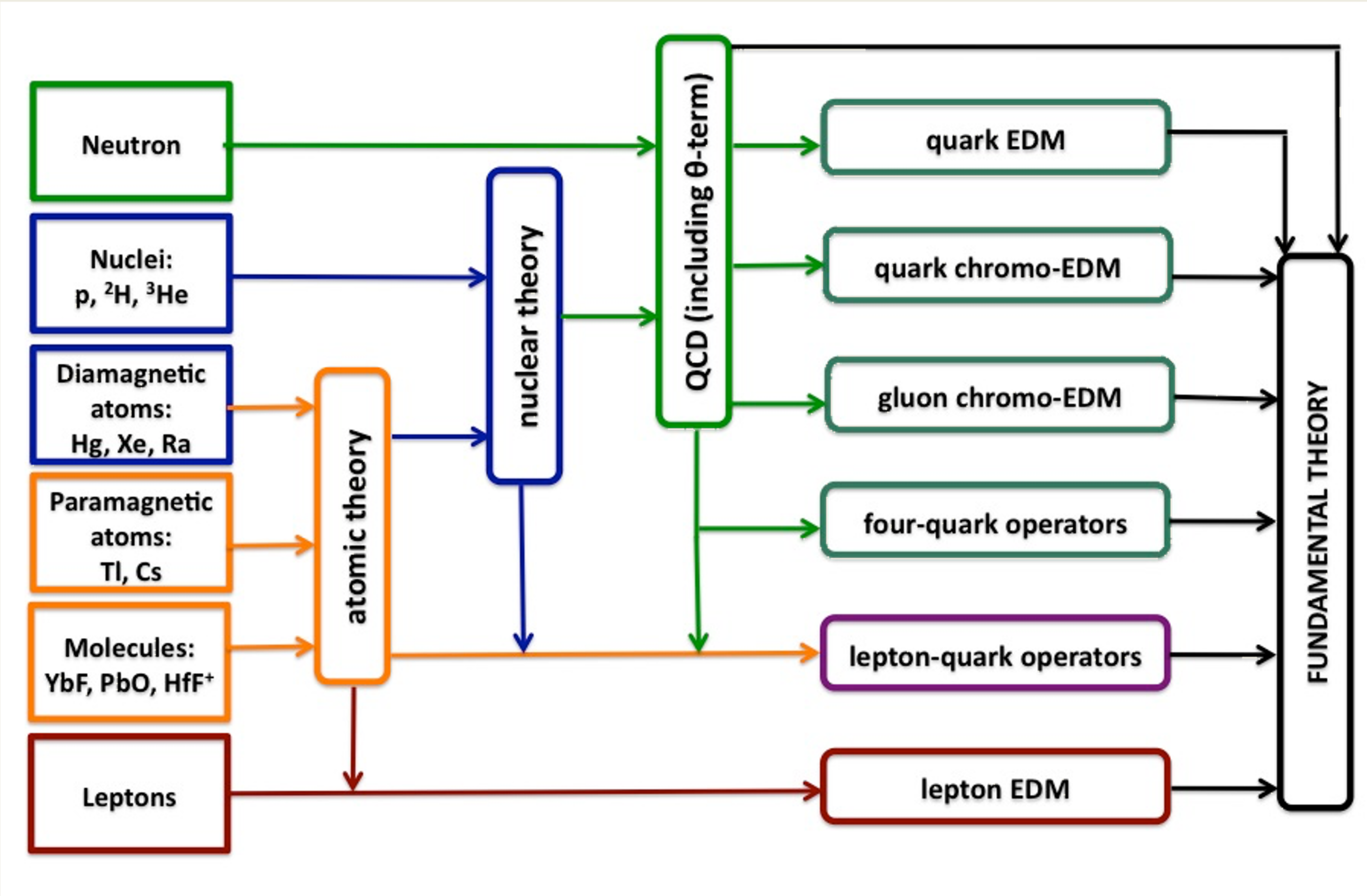
Teamwork

Constraining the $\mathcal{CP}$ structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis

Henning Bahl[1], Elina Fuchs[2,3,4], Sven Heinemeyer[5], Judith Katzy[6], Marco Menen[4,7,8], Krisztian Peters[6], Matthias Saimpert[9], Georg Weiglein[6,10]

- Low-energy limits avoided in global fits (free directions)
- **Future of BSM searches: inclusive low- and high-energy probes**

The EDM metromap



Conclusion/Summary/Outlook

Standard Model Effective field theory

- ✓ If BSM physics is assumed to be heavy, new fields can be integrated out
- ✓ All experiments we do are then "low-energy experiments"

CP-violation in the Higgs sector

- ✓ CP violation in the SM-EFT can arise from Higgs interactions
- ✓ Interesting experimental footprint and relevant for baryogenesis

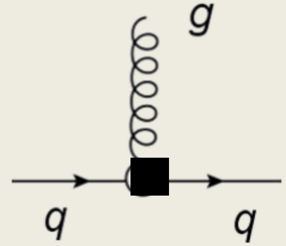
Use all experimental information

- ✓ Low- and high-energy experiments very complementary !

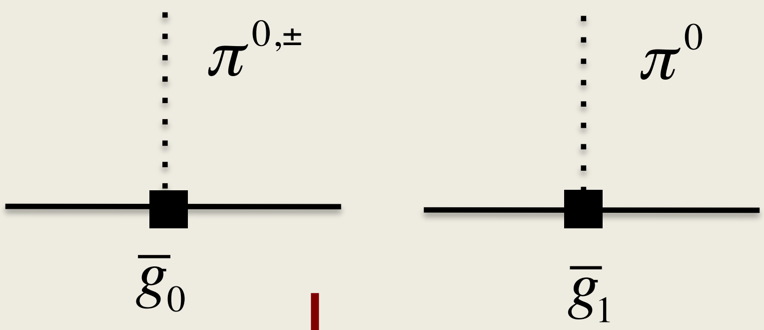
- ✓ EDMs just an example, similar program for other fundamental symmetries (e.g. Lepton number and neutrinoless double beta decay)

Hadronic CP violation

- **Example: quark chromo-EDM**

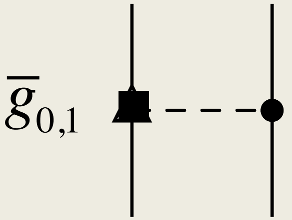


- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**

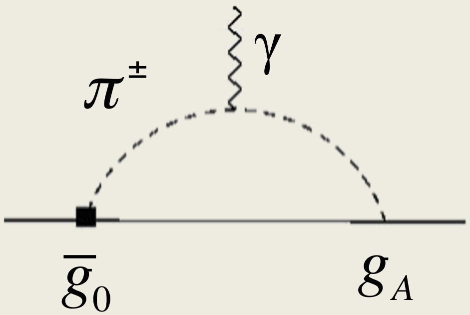


Tree

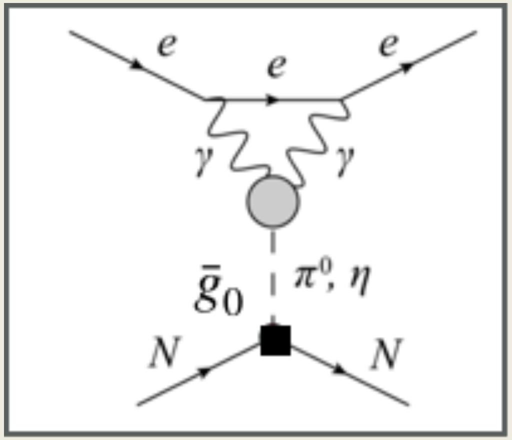
CP-odd nuclear force



1-Loop
Neutron EDM



CP-odd electron-nucleon interactions



Pospelov et al '20

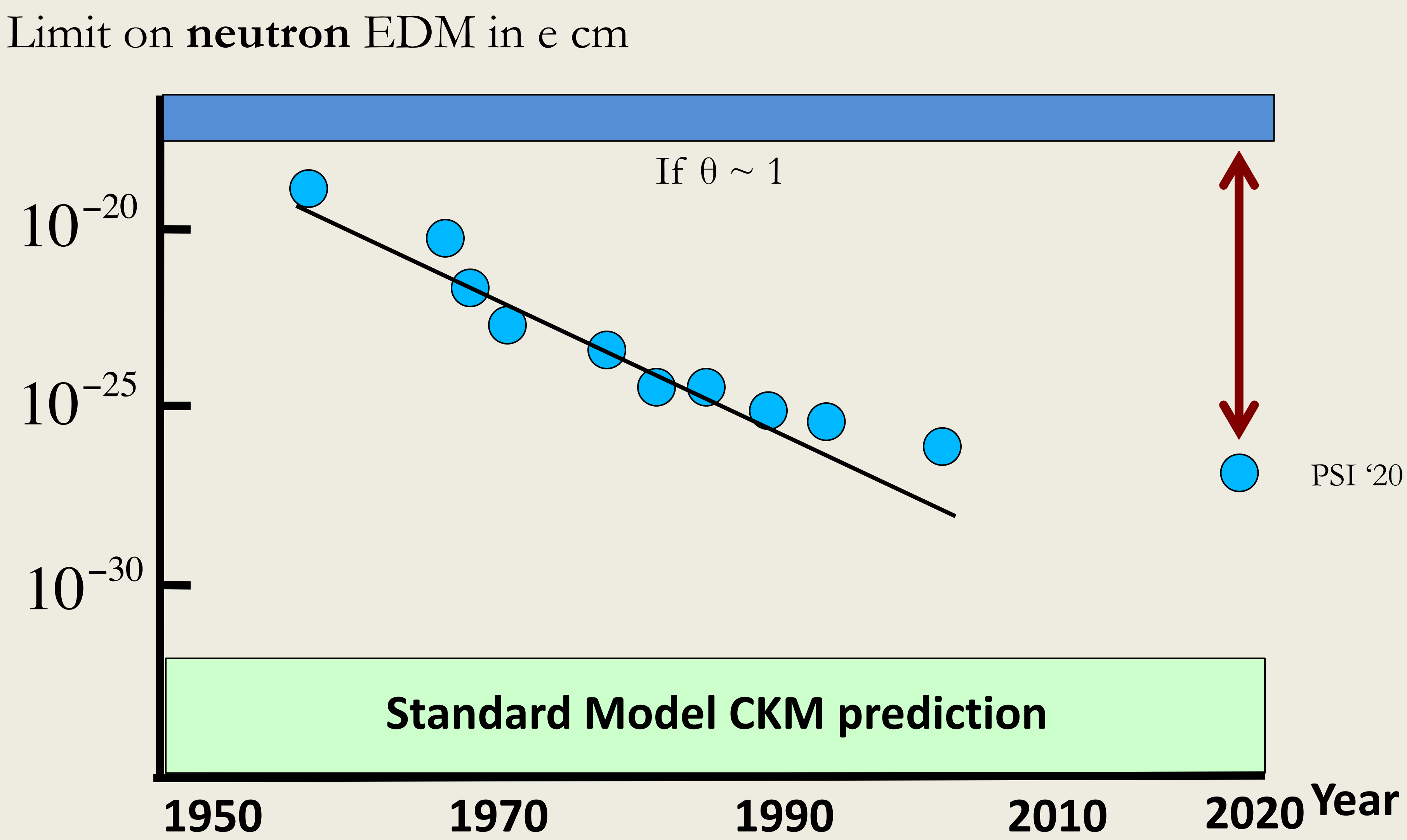
A second source of CP violation

1. **There is another source of CP violation in the Standard Model**

$$+\theta \frac{g_s^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G^{\mu\nu} \quad \xleftrightarrow{\text{axial U(1) transformation}} \quad -\left(\frac{m_u m_d}{m_u + m_d}\right)\theta\, \bar{q} i\gamma^5 q$$

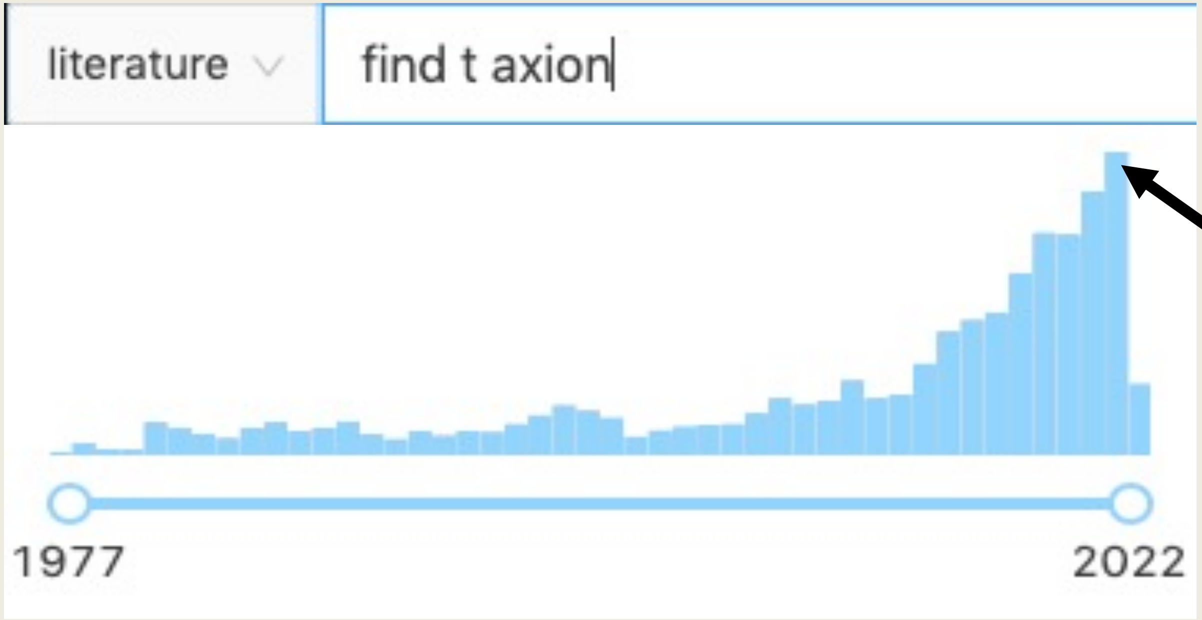
Theta itself is unknown → **Have to measure it**

A second source of CP violation



Strong CP problem: $\theta < 10^{-10}$

A second source of CP violation



341 papers

Theta itself is unknown → **Have to measure it** **$\theta < 10^{-10}$**

This is called the strong CP problem (driven by EDM searches)

Lead to a lot of theorizing: popular solutions are **axions**
(could be dark matter)